

Computer Assisted Deformity Correction using the Taylor Spatial Frame (TSF)

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1 Abstract

The management of multiapical and multidirectional deformities of the lower limb due to different aetiologies is still a challenging task for the orthopaedic surgeon.

Internal fixation techniques for deformity correction are normally combined with open osteotomies and acute correction. For complex deformities these methods are restricted by several factors, particularly when additional leg length discrepancy has to be corrected.

In the last decades external fixators, especially the circular Ilizarov fixator, have become popular to correct complex deformities and perform bone lengthening.

Despite several advantages, each Ilizarov frame is a special, custom-made construct for a given case. Treatment of multiaxial and especially rotational deformities may be difficult and time-consuming postoperatively due to frame adjustments.

The Taylor Spatial Frame was introduced in 1994 and became popular in the following years. It is a modular circular external fixation system using the same methods of frame attachment and the same gradual correction principles as the Ilizarov device.

It consists of two rings or 2/3 rings connected by six telescopic struts. In conjunction with an internet based software program a virtual hinge can be created to correct simple and most complex deformities with the same frame.

By adjusting only the strut length, calculated by the software, the TSF allows simultaneous six-axis correction without frame modification, even residual deformities may be restored with a second program without any reoperation. Different modes of the software program are available; the Total Residual Program is most helpful.

Despite using the same principles for callus distraction as the Ilizarov device, the computer-operated TSF allows a great number of advantages: The handling of the frame is less time consuming, no difficult changes of hinges are necessary. The duration of the correction time is predictable due to the prescription site, and what's most important the results of treatment are more accurate than the Ilizarov device as shown in a study.

In 1999 at the Orthopaedic Hospital Vienna-Speising we started to change from the Ilizarov system to the Taylor Spatial Frame for treatment of complex deformities and leg lengthening.

From June 1999 to February 2009 we were able to perform correction of 501 segments with the TSF- system. The patients suffered from congenital and hereditary disorders (Congenital Femoral Deficiency, Fibular Hemimelia, Hypophosphataemia, Skeletal Dysplasia, Achondroplasia, Enchondromatosis, Osteochondromas), after infections and trauma with deformity and growth disturbance and from idiopathic disorders.

For treatment single and multilevel corrections were performed.

The results of follow-up studies have encouraged us to use this new external fixation system.

The Taylor Spatial Frame offers the experienced surgeon an accurate and reproducible correction technique with several advantages compared to previously used devices.

2 Introduction

2.1 History of External Fixation

Modern techniques of callus distraction started with the work of Codivilla⁹ at the beginning of the 20th century. In 1904 he reported his first experiences with femoral lengthening.

Subsequently, different improvements were described in the following decades⁵⁹ by various authors. In 1921 Putti⁴⁷ described the need for a gradual, controlled lengthening technique, but his frame was not rigid enough.

Abbott¹ constructed a more stable frame in 1924, he started gradual lengthening several days postoperatively. Nevertheless, various complications were described. In 1944 Wittmoser⁶⁰ developed a ring fixator for lengthening of the tibia and fibula, which solved most of the earlier mechanical problems.

The introduction of the Ilizarov-Ringfixator by G.A. Ilizarov in the early 1950's significantly influenced the further development²⁵⁻²⁸. By using circular rings fixed with transosseous wires the device allows bone lengthening, fracture healing and deformity correction in any dimension.

In 1963 Wagner⁵⁸ developed a unilateral fixator mounted with transosseous half-pins. After osteotomy he lengthened with a distraction rate of 2-4 mm per day, after correction bone grafting and plating was performed. Due to the nonbiologic distraction rate a lot of complications like poor callus formation, non-union and hardware failure could be observed.

The unilateral Orthofix device was introduced by De Bastiani and co-authors in 1987¹². This fixator allows lengthening, axial correction and dynamization of the regenerate bone.

The Taylor Spatial Frame, a circular hexapod system, was developed by J.C. and H.S. Taylor in 1994⁵⁵. The frame uses the same methods of frame attachment and the same principles of gradual correction as the Ilizarov device. Due to a software program a six-axis correction is possible. The system became very popular in the last decade.

2.2 Principles of Callus Distraction

Distraction osteogenesis is a method for regenerating new bone formation. As introduced by Ilizarov, gradual mechanical distraction after low-energy osteotomy produces new bone formation.

Ideal conditions are a stable fixation, an osteotomy in the metaphyseal area, followed by a waiting period of five to seven days. The distraction rate should be 1 mm / day in several steps. Under these conditions undifferentiated mesenchymal cells generate osteoblasts and then build collagen and an osteoid matrix. Finally new bone formation is produced, surrounded by blood vessels, orientated parallel to the distraction force. So the regenerate bone can successfully bridge the gap ².

The amount of lengthening is limited by the preservation of normal joint function and limited soft tissue growth.

Unstable fixation and an increased distraction rate more than 2 mm / day can lead to poor callus formation and non-union. A prolonged latency after osteotomy may result in a premature consolidation.

The stability of the ring system depends on the number of wires and half-pins, their diameter, the angle of each one to another, the wire tension and the bone quality.

The wire diameter should be 1.5 – 1.8 mm, the tension should be between 110 and 130 kp of force for full rings. The fixation points are dependent on the anatomical situation and the type of deformity ³⁰.

The ideal site for the corticotomy is the metaphyseal area ². It is performed percutaneously to preserve blood supply. After pre-drilling, the corticotomy is completed with an osteotome.

After complete consolidation of the new bone formation the frame can be removed, partial weight-bearing should be performed for some weeks.

2.3 Normal Lower Limb Alignment

When dealing with deformities, it is first important to understand the parameters of normal alignment. Two main aspects have to be taken into consideration: joint alignment and joint orientation^{24,42,43,52}. Joint alignment refers to the colinearity of the hip, knee and ankle joint in normal limbs. Joint orientation refers to the orientation of each articular surface with respect to the axis of the individual limb segment (femur or tibia).

For each long bone of the lower limb a mechanical and anatomic axis line can be defined in the frontal and sagittal plane.

The mechanical axis line of the femur connects the center of the hip joint and the center of the knee joint; the mechanical axis line of the tibia connects the center of the knee joint and the center of the ankle joint.

The anatomic axes of the femur and the tibia are oriented towards the shaft of these bones. In the frontal plane the anatomical axes of femur and tibia are straight mid-diaphyseal lines.

Because of the femoral neck and the therefore femoral head offset, the mechanical and anatomical axes of the femur are not parallel in the frontal plane and intersect distally. The normal femoral anatomic-mechanical angle (AMA) is $7 \pm 2^\circ$.

In the tibia, the mechanical and anatomical axes are parallel with a displacement of a few millimeters.

The orientation of the hip, knee and ankle joint relating to the frontal and sagittal plane can be described by the use of joint orientation lines. The hip joint orientation line in the frontal plane is a line passing through the center of the femoral head and the proximal tip of the greater trochanter. The femoral knee joint orientation line in the frontal plane is drawn tangentially to the most convex points of the medial and lateral femoral condyle. In the lateral plane it passes through the two points where the femoral condyles meet the anterior and posterior metaphyseal contour.

The tibial knee joint orientation line in the frontal plane connects two points of the tibial plateau subchondral line; in the sagittal plane the line is drawn along the flat portion of the subchondral bone.

The tibial ankle joint orientation line in the frontal plane is drawn across the tibial plafond; in the lateral plane it passes through the distal tip of the anterior and posterior tibial lip. (Fig.1)

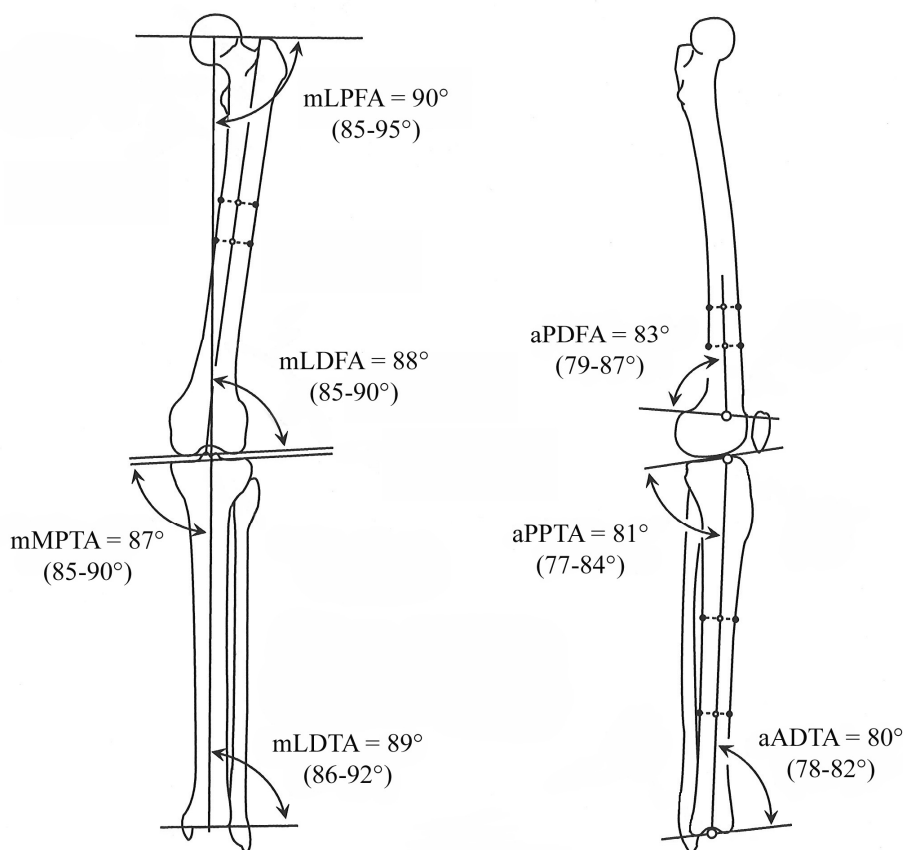


Fig. 1: Mechanical and anatomical axes of femur and tibia and joint orientation angles

The joint lines in the frontal and sagittal plane have a characteristic orientation to the mechanical and anatomical axes. Nowadays the Paley nomenclature is mostly used to name these angles^{39,41}. The names are termed according to the relation to a mechanical or an anatomical axis, to the location on the bone and to the orientation in the frontal or sagittal plane (Fig. 2, Fig. 3).

1.	mechanical or anatomical
2.	lateral or medial / anterior or posterior
3.	proximal or distal
4.	bone (femur or tibia)
5.	angle

Fig. 2: Guideline for angle abbreviations

NSA	Neck shaft angle
mLPFA	Mechanical lateral proximal femoral angle
aMPFA	Anatomical medial femoral angle
aLDFA	Anatomical lateral distal femoral angle
mLDFA	Mechanical lateral distal femoral angle
JLCA	Joint line convergence angle
MAD	Mechanical axis deviation
mMPTA	Mechanical medial proximal tibial angle
mLDTA	Mechanical lateral distal tibial angle
aPDFA	Anatomical posterior distal femoral angle
aPPTA	Anatomical posterior proximal tibial angle
aADTA	Anatomical anterior distal tibial angle

Fig. 3: Angle abbreviations

2.4 Consequences of Malalignment of the Lower Extremities

A relationship of malalignment and degenerative osteoarthritis may be obvious, but the natural history of the process has not been adequately documented. Prospective data are not available. Pauwels⁴⁵ was one of the first who recognized the importance of biomechanics and its relationship to preoperative planning for deformity correction. Static malalignment is well documented on standing radiographs, but clinically the situation is more complex. Joint instability, muscle contractures and pathological gait patterns have been taken into consideration.

Several retrospective clinical studies^{29,35,37} suggest an association between malalignment and degenerative arthropathy, especially at the knee joint. When the mechanical axis passes the knee joint more medially or laterally, pathological forces are increased at the medial or lateral compartment. But most of these studies have their limitations and are difficult to interpret.

Although direct clinical evidence between malalignment and osteoarthritis has not been possible, the reestablishing of joint alignment and joint orientation is an accepted goal of deformity correction³⁹.

2.5 Indications for Deformity Correction

The management of deformities due to different etiologies is still a challenging task facing the orthopedic surgeon. It is not only a problem of altered joint loading through various combinations of frontal, sagittal and rotational deformities and therefore the danger of premature osteoarthritis. Patients also have to deal with esthetic problems, a limited range of joint motion and pathologic gait pattern.

Leg length difference is not an uncommon additional deformity. The consequence is an increased coverage of the femoral head at the shorter side and a decreased coverage at the longer side. Length difference leads to pelvic obliquity and scoliosis of the spine to the shorter side. Low back pain may be a result of muscular asymmetry and disturbance of the iliosacral joint in differences more than 2 cm, therefore in this case correction should be performed either by conservative or

operative procedures ⁴⁶. In differences less than 2 cm back pain could not be seen more often than in control groups ²¹.

It is critical to determine an absolute angular value of the deformity in the frontal or sagittal plane as an indication for surgical correction. Associated translation and the level of the deformity have to be considered. If the apex of the deformity is close to the knee joint, an enormous effect to the mechanical axis can be expected, whereas deformities close to the hip or ankle joint have far less effects ⁴³.

Deformity corrections can be performed by different methods of fixation, internal and external procedures are available. The choice of hardware is dependent on various factors: age of the patient (open growth plate), level and number of osteotomies, type of osteotomy, acute or gradual correction, bone-, soft tissue- and joint factors ³⁹.

Internal fixation is typically combined with open osteotomy and acute correction ^{8,36,51,61}. This technique has to be considered suitable for correcting deformities of lesser magnitude. Poor bone and soft-tissue structures or neurovascular structures may limit internal methods with acute correction. Additionally, suboptimal intraoperative correction may result in residual deformity.

In case of complex, mostly multiapical deformities the use of external fixators is often indicated ^{3,14,49,50,57}. With these devices an additional leg length difference can be corrected simultaneously. By the use of gradual correction also soft-tissue compromise may be present, residual deformities can be corrected simply by frame adjustments without reoperation.

Various diseases and syndromes may result in deformities of the lower extremities, each of them have their own properties, which have to be considered.

2.5.1 Congenital Deformities

Congenital femoral deficiency, fibular hemimelia and tibial hemimelia are the most important diseases in this group. We have to deal with a wide spectrum of bony deformities and deficiencies of variable degree, which are present at birth.

Bone malorientation and malrotation have to be considered, especially hypoplasia of the lateral femoral condyle in width and height and horizontal deficiency of the lateral tibial condyle resulting in valgus deformity ³⁴. Associated abnormalities often influence the stability and mobility of the hip, knee and ankle joint ⁴⁴.

Especially at the knee joint, anteroposterior instability and patella pathology can worsen the outcome of lengthening and deformity correction. Congenital absence of the anterior and the posterior cruciate ligament alter the shape of the femoral notch and the tibial tubercle, which can be classified by radiograms ³³. Also soft tissue contractures have to be taken into consideration.

2.5.2 Posttraumatic Deformities

Posttraumatic malunion or nonunion of the femur or tibia can be seen with or without leg length discrepancy. Soft-tissue problems are rather infrequent at the femur, whereas poor soft-tissue coverage at the tibia may contribute to postoperative complications.

In premature bones diaphyseal fractures have a tendency to remodel. Metaphyseal and epiphyseal fractures are most frequently combined with injury of the growth plate. Premature growth arrest acts as a tether and constrains normal growth. In case of complete physeal arrest only leg length difference will result, whereas in partial arrest of the growth plate both leg length discrepancy and angular deformity will develop. Injuries of the growth plate are progressive during childhood and adolescence.

Nonunions can be classified as hypertrophic with adequate vascularity and callus formation or atrophic. Bone loss and the presence of infection have to be taken into consideration.

2.5.3 Postinfectious Deformities

Osteomyelitis is an infection of bones including the intramedullary canal and the periosteum. During growth a haematogenic infection is most common. Frequently involvement of the metaphysis is to be observed, the growth plate and even joints can be affected. After infection osseous bars can appear at the level of the growth plate, resulting in axial deformities, leg length difference and severe joint abnormalities.

2.5.4 Hereditary Deformities

Several attempts have been undertaken to find a useful classification of this heterogeneous group of syndromes and diseases. Recently the Committee on Nomenclature on Intrinsic Diseases of Bones gave advice for classification ²².

A genetic cause is discussed in most disorders.

Different diseases are summarized like achondroplasia, diastrophic dwarfism, spondylo-,meta-,epiphyseal dysplasia, mucopolysaccharidosis, osteogenesis imperfecta, different forms of rickets, osteochondromas, enchondromatosis and several other disorders.

All of these syndromes may lead to short stature, leg length difference, axial deformities and joint pathology.

2.5.5 Other Indications

Various etiologies for deformity correction are summarized: Idiopathic varus or valgus deformities of the lower extremity, rotational malalignment syndrome, joint contractures, foot deformities and axial deviations due to unicompartimental osteoarthritis.

3. Materials and Patients

3.1 Malalignment Test (MAT)

The mechanical axis is a line starting from the center of the hip to the center of the ankle joint. Normally this line passes immediately medial to the center of the knee joint (4 – 14 mm medial) ^{24,39}. The perpendicular distance from the mechanical axis line to the center of the knee is called Mechanical Axis Deviation (MAD).

Abnormal MAD affects the knee, hip and ankle joint and leads to the loss of collinearity of these joints in the frontal plane.

Frontal plane malalignment can be caused by femoral or tibial frontal plane deformity or by frontal plane knee joint laxity or dislocation.

To identify the true source of the apex of the deformity, Paley and Tetsworth designed the so called Malalignment Test (MAT) ^{42,43}. Four steps have to be performed using a long standing AP-radiograph (Fig. 4):

Step 0: Measurement of the MAD: Draw the mechanical axis of the lower limb.

Measure the perpendicular distance from the center of the knee to the mechanical axis. The normal range of MAD is 4 – 14 mm medial.

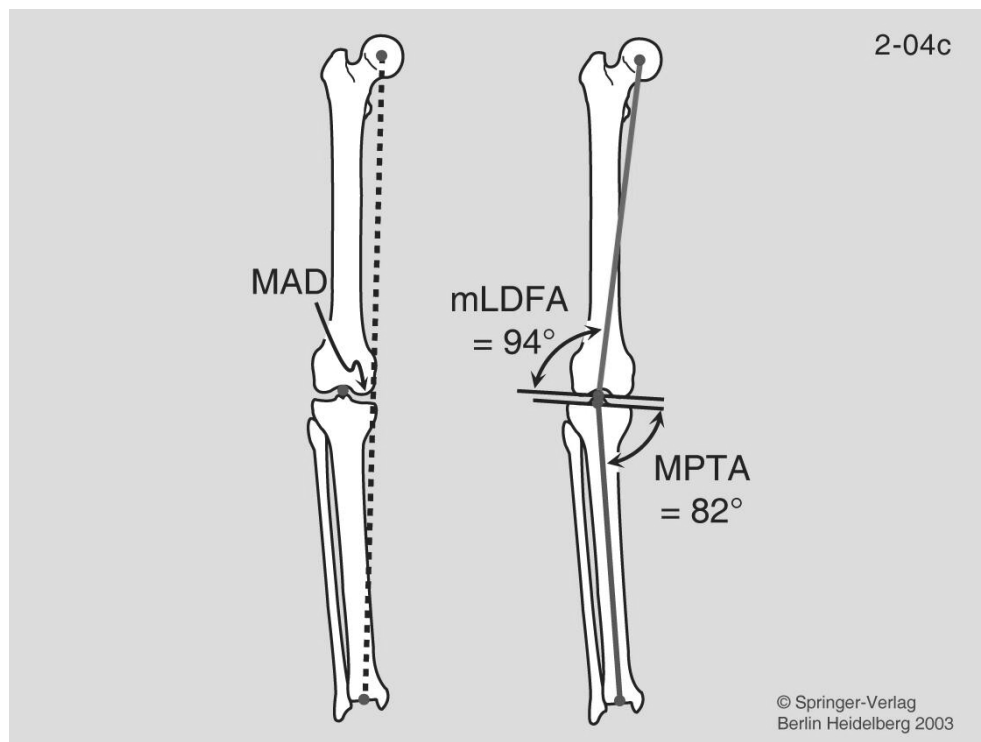
Step 1: Measurement of the mLDFA (mechanical Lateral Distal Femoral Angle):

Angle between the mechanical axis line of the femur and the distal lateral femoral knee joint line. If the mLDFA is outside the physiological range (85° - 90°), the femur is contributing to the MAD.

Step 2: Measurement of the MPTA (Medial Proximal Tibial Angle): Angle between the mechanical axis line of the tibia and the medial tibial knee joint line. If the MPTA is outside the physiological range (85° - 90°), the tibia contributes to the MAD.

Step 3: Measurement of the JLCA (Joint Line Convergence Angle): Angle between the femoral and tibial knee joint lines. Normally these two lines are parallel within 2°. Ligamentous laxity or loss of cartilage can change the JLCA. If the JLCA is outside the physiological range, it can contribute to varus or valgus deformity.

Additionally knee joint subluxation or condylar malalignment can contribute to MAD.



(Diagrams were taken from D. Paley, Principles of Deformity Correction, Springer-Verlag, with friendly permission of Springer-Verlag Heidelberg, Germany)

Fig. 4: Malalignment Test: Deformity femur and tibia

Sagittal plane malalignment can be measured in lateral view radiographs. A line is drawn from the center of the hip to the center of the ankle joint. With the knee in full extension the line normally passes the knee anterior to the center of rotation. With this test flexion or extension malalignment in the sagittal plane can be detected. Compensatory range of motion of the knee can weight the result of the sagittal MAT.

Each joint has a normal anatomical orientation to the mechanical and anatomical axes. Malorientation of the knee leads to MAD. The MAT is therefore a malorientation test of the knee. Malorientation of the hip or the ankle joint usually has lesser consequences on the alignment because these deformities are near to the end of the mechanical axis. Therefore the MAT does not reliably identify such a deformity³⁹.

A separate malorientation test (MOT) is necessary to determine the normal orientation of the hip and ankle joint (Fig. 5).

MOT of the hip: The joint orientation line of the hip can be described relative to the mechanical or anatomical axis line. If the Lateral Proximal Femoral Angle (LPFA) is outside the normal range of $90^\circ \pm 5^\circ$, the hip joint is malorientated to the mechanical axis of the femur. If the Medial Proximal Femoral Angle (MPFA) is outside the normal range of $84^\circ \pm 5^\circ$, the hip joint is malorientated to the anatomical axis of the femur⁵².

MOT of the ankle joint: If the Lateral Distal Tibial Angle (LDTA) is outside the normal range of $89^\circ \pm 3^\circ$, the ankle joint is malorientated to the mechanical axis of the tibia.

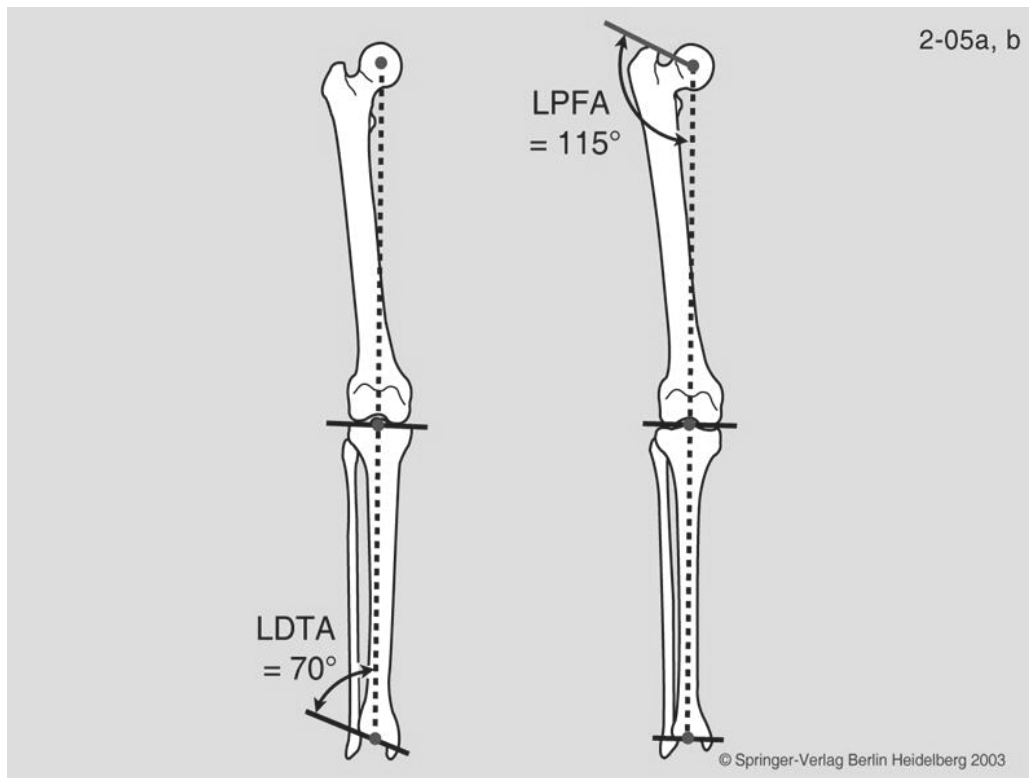


Fig. 5: Left side: Malorientation of the ankle joint: LDTA outside normal range.

Right side: Malorientation of the hip: LPFA outside normal range.

3.1.1 Planning of Frontal Plane Deformities

Angular deviations of the femur or tibia induce angulation of the bone, but also of its axes. When a bone is angulated, its mechanical and anatomical axes are also angulated and divided into a proximal and distal segment. The proximal and the distal line intersect in the so called Center of Rotation of Angulation (CORA) and form an angle, which characterizes the magnitude of the deformity. The CORA can appear at any level of the bone.

Anatomical and mechanical planning methods are used to find the level of the CORA. Before performing these methods, the malalignment test has to be used to determine whether MAD is present and to localize the source of the deformity (Step 0).

Mechanical axis planning of tibial deformities: 3 steps have to be performed ³⁹:

Step 1: The proximal mechanical axis line of the tibia is drawn:

- A: If the ipsilateral mLDFA is normal, just extend the mechanical axis of the femur distally through the center of the knee to get the proximal tibial mechanical axis line (Fig. 6).
- B: If the ipsilateral mLDFA is abnormal, but the contralateral MPTA is normal, then use this angle to draw the proximal tibial mechanical axis line.
- C: If both angles (mLDFA and MPTA) are outside normal range, use the average normal MPTA of 87° instead.

Step 2: The distal mechanical axis line of the tibia is drawn and the MOT of the ankle is performed:

- A: In a normal distal tibial diaphysis draw a mid-diaphyseal line starting from the center of the ankle joint. Measure the LDFA to confirm that it is normal (Fig. 7).
- B: In case of distal tibial deformity with a small distal segment, use the normal contralateral LDFA to construct the distal tibial mechanical axis line.
- C: In case of distal tibial deformity and abnormal contralateral LDFA, use the normal average LDFA of 90°.

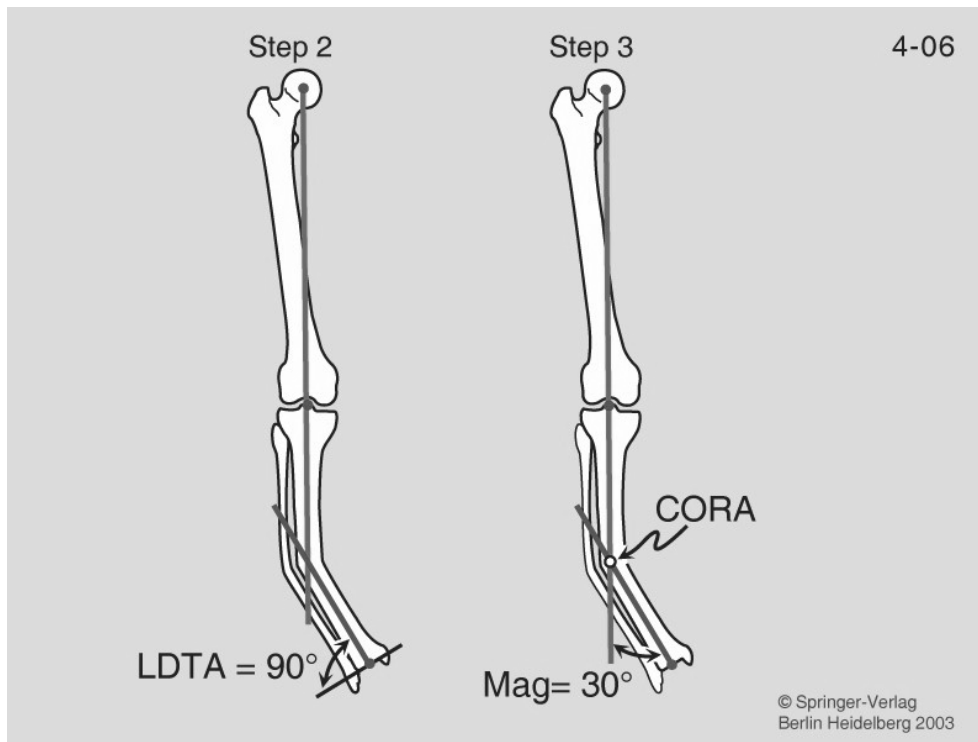


Fig. 7: Step 2A: Draw a mid-diaphyseal distal line. Measure the LDTA.

Step 3A: Mark the CORA and measure the magnitude of angulation.

Anatomic axis planning of tibial deformities: This method is most useful for diaphyseal deformities. The mechanical and the anatomic method are not significantly different from each other, because both axes are rather the same. Using the anatomic method, the mid-diaphyseal lines are drawn first, then the MOT is performed at the knee and ankle joint level.

The anatomic planning is mostly used for posttraumatic deformities, here the goal is to restore the pre-fracture alignment.

Mechanical axis planning of femoral deformities: Again 3 steps have to be performed³⁹. Start with the MAT (Step 0, Fig. 8). There are two differences to the tibial mechanical method: First you start with the distal axis line, second the Anatomic-Mechanical Axis (AMA) of the tibia is 0° , the AMA of the femur is 7° , this makes step 2 more complicated.

Step 1: The distal mechanical axis line of the femur is drawn:

- A: If the ipsilateral MPTA is normal, just extend the mechanical axis of the tibia proximally through the center of the knee to get the distal femoral mechanical axis line (Fig. 9).
- B: If the ipsilateral MPTA is abnormal, but the contralateral mLDFA is normal, then use this angle to draw the distal femoral mechanical axis line.
- C: If both angles (MPTA and mLDFA) are outside normal range, use the average normal mLDFA of 87° instead.

Step 2: The proximal mechanical axis line of the femur is drawn and the MOT of the hip is performed.

- A: If the proximal femur is not deformed, draw a mid-diaphyseal line of the proximal femur followed by a second parallel line through the center of the femoral head. If the contralateral mLDFA is normal, measure the AMA on the normal side. Take this angle and draw a third line to the second one, starting from the center of the hip. The third line is the mechanical axis of the proximal femur (Fig. 9).
- B: If the contralateral mLDFA is abnormal, use the average value for femoral AMA of 7° . The rest is the same as above.
- C: In case of proximal femoral deformity and normal contralateral LPFA use this as a template angle. If the LPFA is abnormal, the normal average LPFA of 90° is used.

Step 3: The CORA is marked and the magnitude of angulation is measured. Decide whether it is a uniapical or multiapical angulation:

- A: If the intersection of the proximal and the distal mechanical axes and the obvious deformity are at the same level, mark this as a uniapical CORA and measure the magnitude of angulation (Fig. 9).
- B: If the CORA does not correspond with the obvious deformity, there is either a second apex of angulation or a translation deformity. When

dealing with a second apex, draw a third line corresponding to the mechanical axis of the middle segment, that intersects the proximal mechanical axis at the level of the obvious deformity producing two CORA's. Measure the magnitude of angulation at both CORA's.

C: If the CORA is at the same level of the obvious deformity and the ipsilateral LPFA is abnormal, there is a second angular deformity at the level of the hip joint. Use the normal contralateral LPFA or the average angle of 90° and draw a third line starting from the center of hip. Measure the magnitude of angulation at both CORA's.

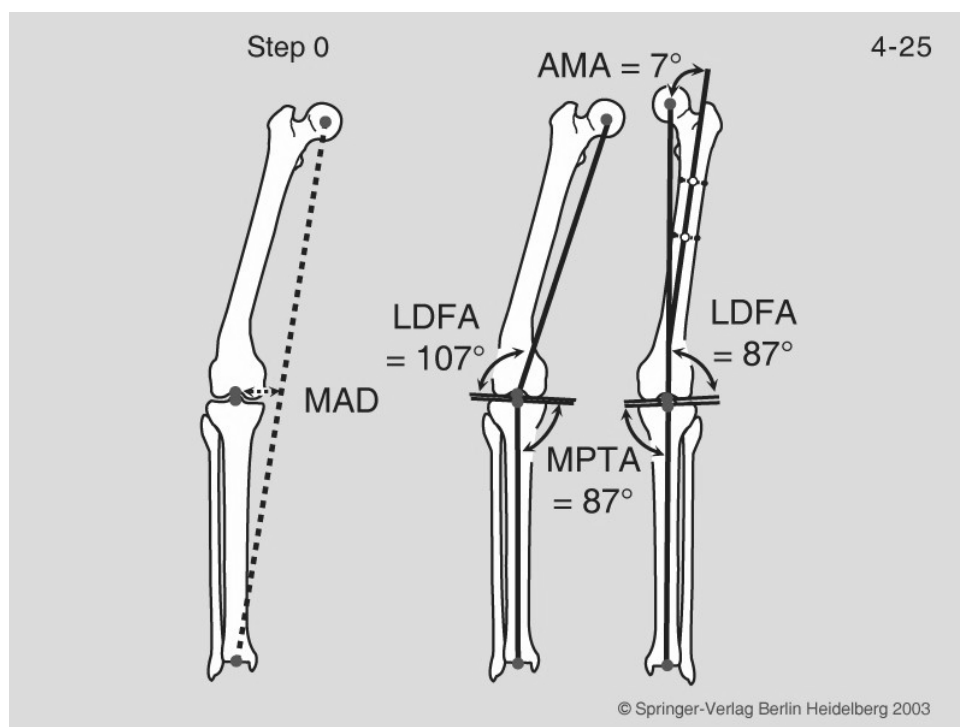


Fig. 8: Step 0: MAT,
Anatomic mechanical angle (AMA) femur: 7°

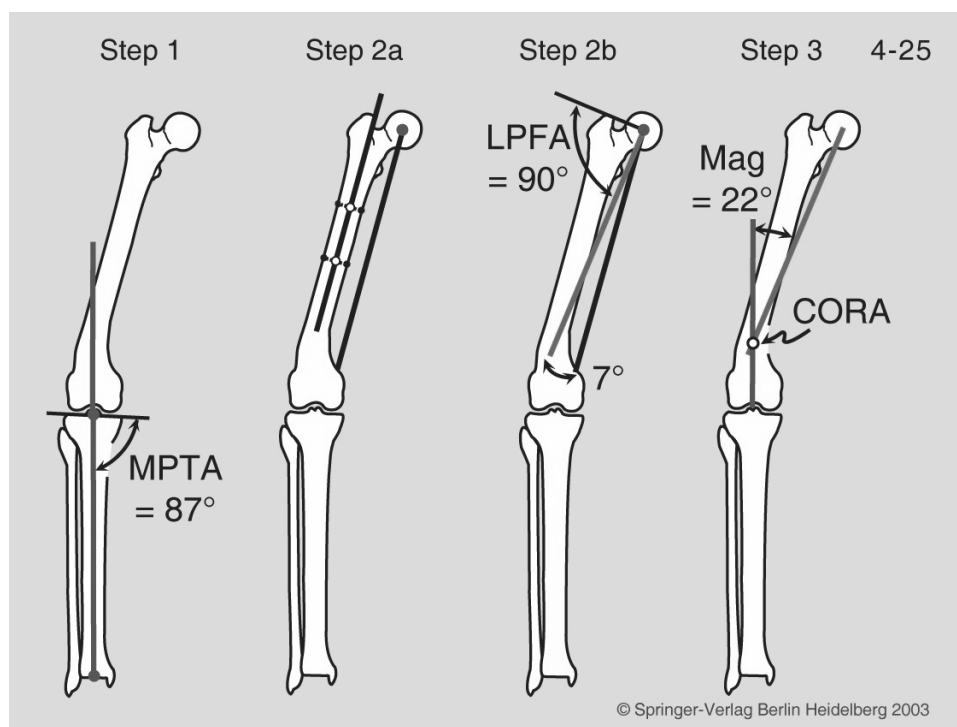


Fig. 9: Step 1A: Extend the mechanical axis of the tibia proximally.

Step 2A: Draw a mid-diaphyseal line and a second parallel line through the center of the femoral head. Draw a third line with an AMA of 7° , starting at the center of the hip.

Step 3A: Mark the CORA and measure the magnitude of angulation.

Anatomic axis planning of femoral deformities: Again 3 Steps are necessary³⁹.

Step 1: Draw the mid-diaphyseal line(s) to represent the diaphysis of the femur.

Perform the MOT of the hip and knee joint and measure the MPFA and the aLDFA (Fig. 10).

Step 2: Determine the values of MPFA and aLDFA.

A.1.: If the aLDFA is normal, there is no additional distal CORA.

A.2.: If the aLDFA is abnormal, draw a distal anatomic axis line starting 1 cm medial to the center point of the knee. Use the normal contralateral aLDFA or the average normal aLDFA of 81° (Fig. 10).

B.1.: If the MPFA is normal, there is no additional proximal CORA.

B.2.: If the MPFA is abnormal, draw a proximal anatomic axis line referenced to the hip joint orientation line. Use the normal contralateral MPFA or the average normal MPFA of 84° .

Step 3: The CORA is marked and the magnitude of angulation is measured. Decide whether it is a uniapical or multiapical angulation:

- A: If the intersection of the proximal and the distal anatomic axes and the obvious deformity are at the same level, mark this as an uniapical CORA and measure the magnitude of angulation (Fig. 10).
- B: If the CORA does not correspond with the obvious deformity, draw a third line resulting in a second CORA. Measure the magnitude of angulation at both CORA's.
- C: Draw the bisector line of the deformity that defines the true level of angulation.

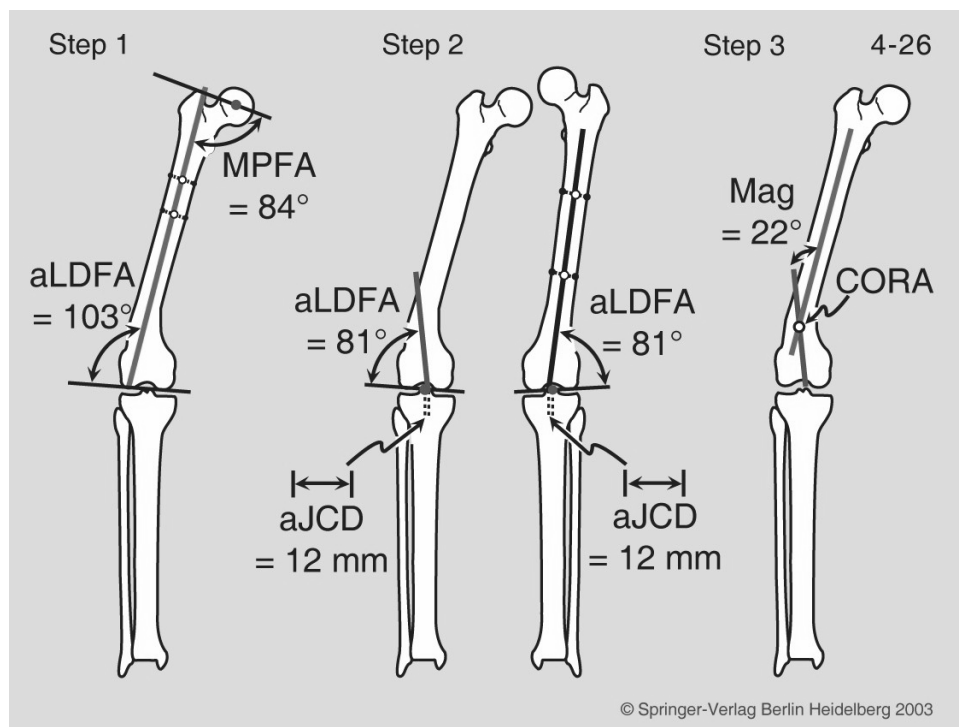


Fig. 10: Step 1: Draw the mid-diaphyseal line, measure MPFA and aLDFA.
 Step 2A.2: Use the normal contralateral aLDFA.
 Step 3A: Mark the CORA and measure the magnitude of angulation.

3.1.2 Planning of Sagittal Plane Deformities

There is a difference in the concept of malalignment in the frontal and the sagittal plane. There is no range of knee joint motion in the frontal plane to compensate mechanical axis deviation. The knee moves in the sagittal plane, therefore the sagittal plane alignment changes during normal gait³⁹.

To determine the mechanical axis of the lower limb in the sagittal plane, a line is drawn from the center of the femoral head to the center of rotation of the ankle. In full extension of the knee joint, the mechanical axis passes anterior to the center of the rotation of the knee. This is an important fact to lock the knee in full extension and relax the extensor muscles.

Sagittal plane knee malalignment, especially for recurvatum deformities, is better tolerated than frontal plane deformities.

Sagittal Plane Malalignment Test:

The purpose of the test is to identify flexion or extension malalignment. Flexion malalignment is present when the mechanical axis passes posterior to the center of rotation of the knee joint, extension malalignment can be seen in hyperextension more than 5°.

The normal joint orientation of femur and tibia is characterized by the Posterior Distal Femoral Angle (PDFA, $83^\circ \pm 4^\circ$), by the Posterior Proximal Tibial Angle (PPTA, $81^\circ \pm 4^\circ$) and by the Anterior Distal Tibial Angle (ADTA, $80^\circ \pm 2^\circ$)^{39,42,43}.

Sagittal plane anatomic axis planning of tibial deformities:

Step 1: Draw the mid-diaphyseal line(s) to represent the diaphysis of the tibia. Perform the MOT of the knee and ankle joint and measure the PPTA and the ADTA (Fig. 11).

Step 2:

- A.1.: If the PPTA is normal, there is no additional proximal CORA.
- A.2.: If the PPTA is abnormal, draw a proximal anatomic axis line starting at a point of one fifth at the knee orientation line. Use the normal contralateral PPTA or the average normal PPTA of 81° .
- B.1.: If the ADTA is normal, there is no additional distal CORA.
- B.2.: If the ADTA is abnormal, draw a distal anatomic axis line

referenced to the ankle joint orientation line. Use the normal contralateral ADTA or the average normal ADTA of 80° .

Step 3: The CORA is marked and the magnitude of angulation is measured. Decide whether it is a uniapical or multiapical angulation:

A: If the intersection of the proximal and the distal anatomic axes and the obvious deformity are at the same level, mark this as a uniapical CORA and measure the magnitude of angulation.

B: If the CORA does not correspond with the obvious deformity, draw a third line resulting in a second CORA. Measure the magnitude of angulation at both CORA's.

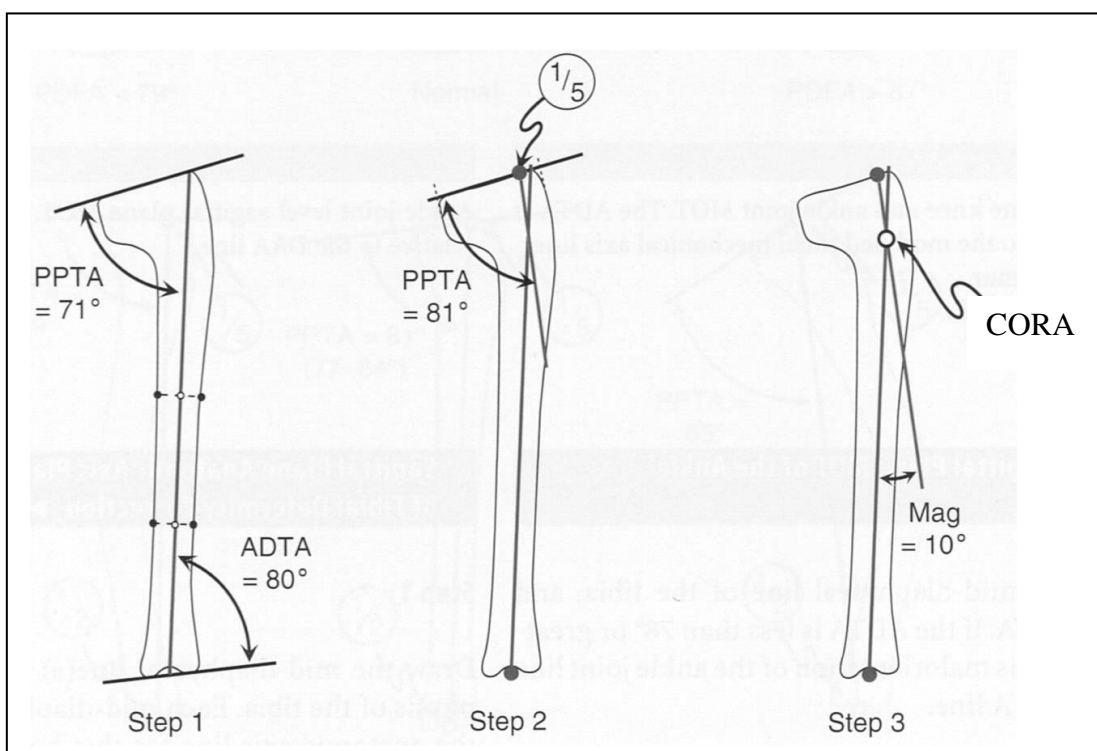


Fig. 11: Step 1: Draw the mid-diaphyseal line, measure PPTA and ADTA.
Step 2: Use the normal contralateral PPTA.
Step 3: Mark the CORA and measure the magnitude of angulation.

Sagittal plane anatomic axis planning of femoral deformities:

- Step 1:** Draw the mid-diaphyseal line(s) to represent the diaphysis of the femur. Perform the MOT of the knee joint and measure the PDFA (Fig. 12).
- Step 2:** A: If the PDFA is normal, there is no additional distal CORA.
B: If the PDFA is abnormal, draw a distal anatomic axis line referenced to the knee joint orientation line. Use the normal contralateral PDFA or the average normal PDFA of 83°.
- Step 3:** The CORA is marked and the magnitude of angulation is measured. Decide whether it is a uniapical or multiapical angulation:
A: If the intersection of the proximal and the distal anatomic axes and the obvious deformity are at the same level, mark this as a uniapical CORA and measure the magnitude of angulation.
B: If the CORA does not correspond with the obvious deformity, draw a third line resulting in a second CORA. Measure the magnitude of angulation at both CORA's.

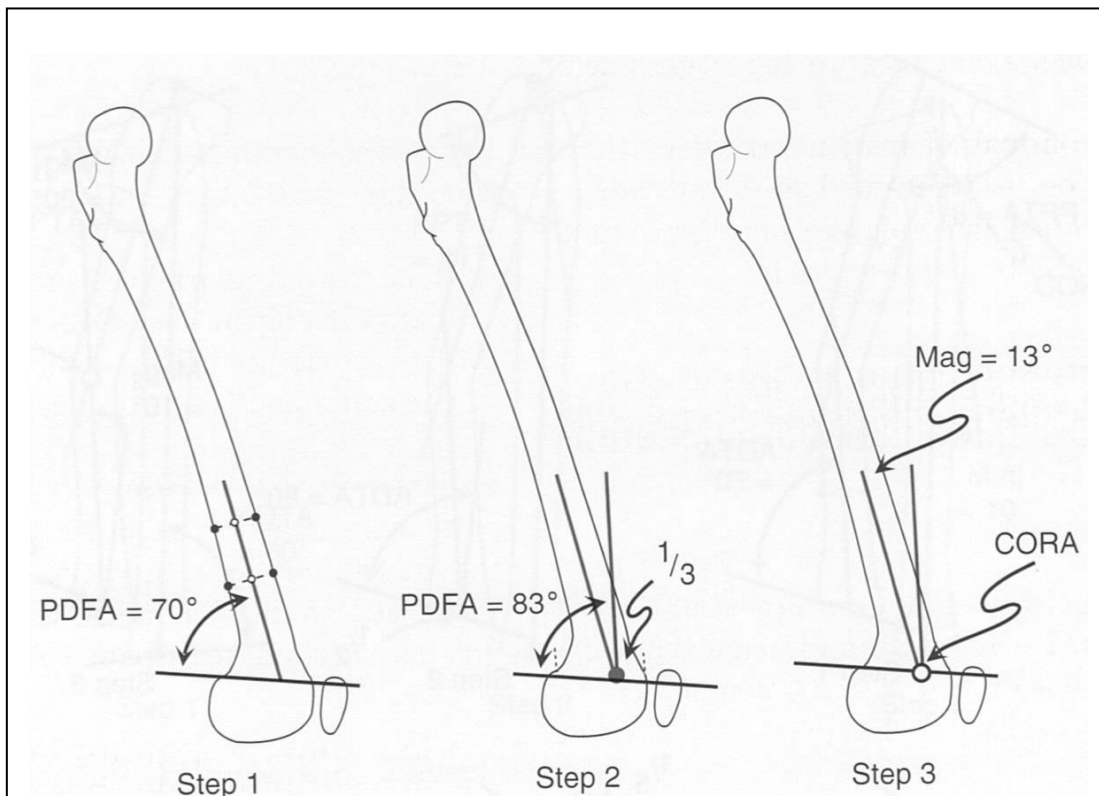


Fig. 12: Step 1: Draw the mid-diaphyseal line, measure PDFA.
 Step 2: Use the normal contralateral PDFA.
 Step 3: Mark the CORA and measure the magnitude of angulation.

3.1.3 Osteotomy rules

Two basic osteotomy types for angular deformity correction can be defined: (1) angulation osteotomies and (2) angulation and translation osteotomies. The correction is performed around the Angulation Correction Axis (ACA). If the ACA is at the same level of the osteotomy, an open or closed wedge angulation will result at the level of the osteotomy. If the ACA is at a different level from the osteotomy line, an angulation and translation will occur at the osteotomy site ³⁹.

Osteotomy rule 1 (according to Paley): When the osteotomy and the ACA pass through the CORA (Center of rotation of angulation) realignment occurs just with angulation without translation. An open or closed wedge osteotomy can result (Fig. 13).

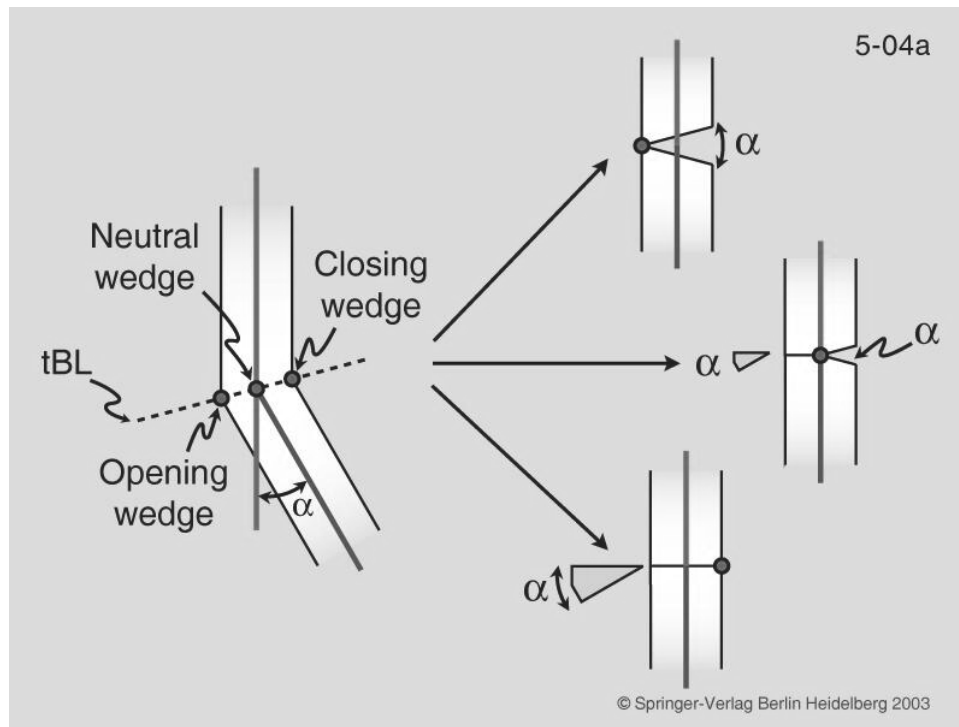


Fig. 13: Osteotomy rule 1

Osteotomy rule 2: When the ACA is through the CORA but the osteotomy is at a different level, the axis will realign by angulation and translation at the osteotomy site (Fig. 14).

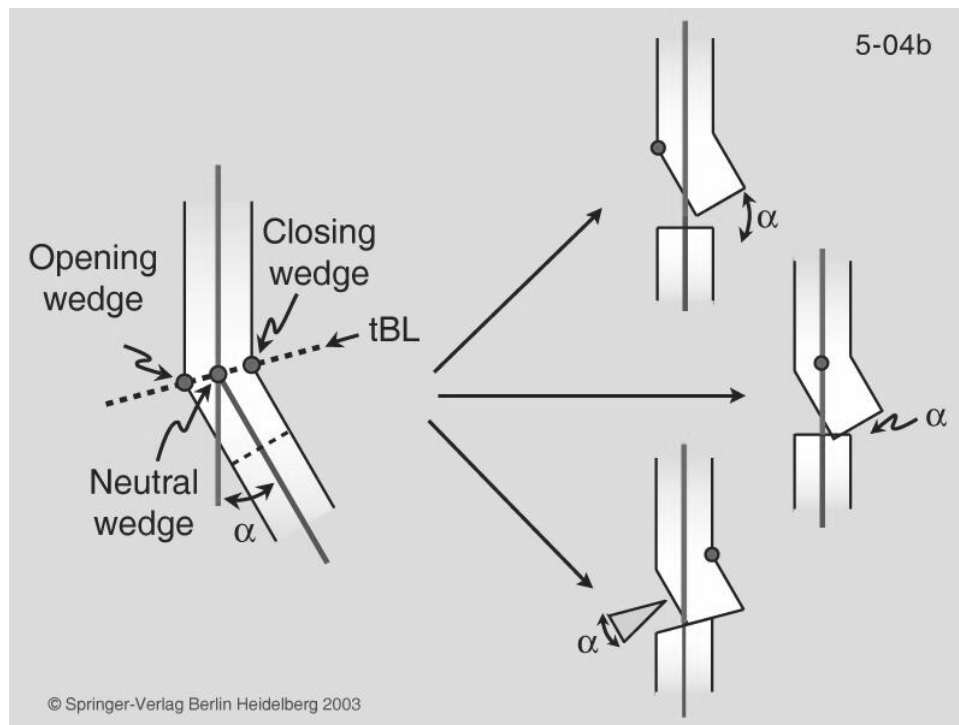


Fig. 14: Osteotomy rule 2

Osteotomy rule 3: When the osteotomy and the ACA are at a level above or below the CORA, a translation deformity will result at the osteotomy site (Fig. 15).

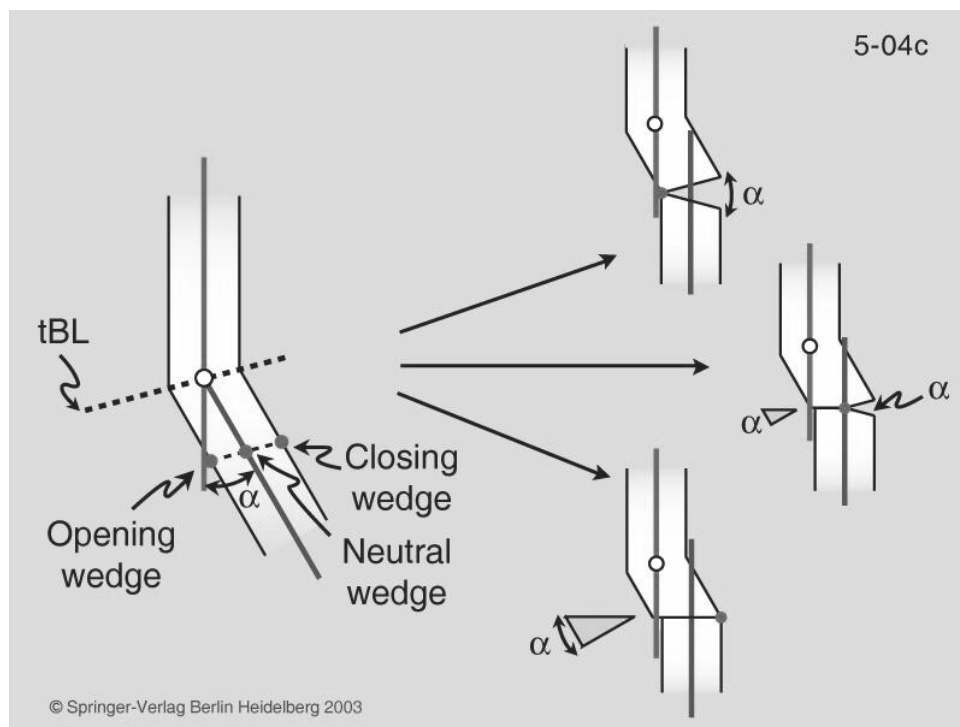


Fig. 15: Osteotomy rule 3

3.1.4 Radiological Assessment

To measure frontal plane alignment, long standing radiographs of both lower extremities are preferred for the anterior-posterior view. The true AP view is obtained with the patella in a straight forward position, irrespective of the foot position. In case of patella dislocation the knee flexion-extension axis should be parallel to X-ray film. If there is a leg length difference, the discrepancy should be compensated with blocks to avoid mistakes due to compensatory mechanisms such as contralateral knee flexion³⁹.

Lateral view radiographs of the femur and the tibia are used to measure the axes in the sagittal plane. It is also important to perform a true lateral view of the knee in full extension, to analyze the relationship of the femur and the tibia.

3.2 The Taylor Spatial Frame (TSF)

The flight simulator in the early 1950s was one of the most elegant applications of the Stuart platform. It uses six struts of adjustable length to move an object in any direction in space.

In 1994 J.C. and H.S. Taylor first applied this method to orthopedics and created the Taylor Spatial Frame (TSF, Smith & Nephew, Memphis, TN, USA).

It is a circular external fixation system, which allows correction of the simplest to the most complex skeletal deformities using the same frame (Fig. 16).

It consists of two full rings or two-third rings connected by six telescopic struts at special universal joints. A two-ring construct can simulate a single-level deformity; a three-ring construct with six struts between each pair of rings can simulate a bi-level deformity.

By adjusting strut length only, one ring can be repositioned with respect to the other to correct all aspects of a six-axis deformity simultaneously.

Strut length adjustments are calculated by an associated web-based software program and can easily be performed by the patient according to a provided daily time schedule.

Hardware: Full rings are available in sizes from 80 to 300 mm internal diameter in 25 mm increments. Two-third rings range from 80 to 275 mm.

The telescopic struts are available in two different types: Standard struts and FastFx struts. The functional length of the Standard struts ranges from 60 to 283 mm in five different sizes, the FastFx struts range from 91 to 311 mm in four different sizes.

The length of the struts is gradually changed by rotating an adjustment knob. The FastFx struts are additionally equipped with an unlock mechanism, which allows rapid change of strut length intraoperatively. Six colored and numbered clips are applied at the struts to allow correct identification.



Fig. 16: Taylor Spatial Frame: Two rings connected by six telescopic struts

3.2.1 Comparison with the Ilizarov Ringfixator

Each Ilizarov fixator is a custom made construction for a given deformity. It uses translation, axial rotation, angulation or angulation-translation devices to correct the deformity. Theoretically the frame allows correction in any dimension; in multiplanar deformities it is sometimes difficult to place the hinges in a perfect position. Especially in combination with rotational deformities a step-by-step procedure is necessary to correct the deformity.

Therefore the handling of the frame can be more time consuming, difficult changes of hinges may be necessary. Translation deformities may occur while correction of rotational deformities.

The TSF can correct simultaneously most complex multiplanar deformities with the same frame construction and the support of a web-based internet program.

It can simulate various Ilizarov frame constructs (Fig. 17a, b).

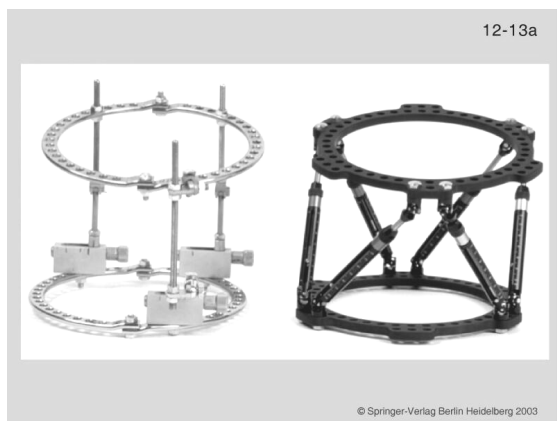


Fig. 17a: Ilizarov translation device

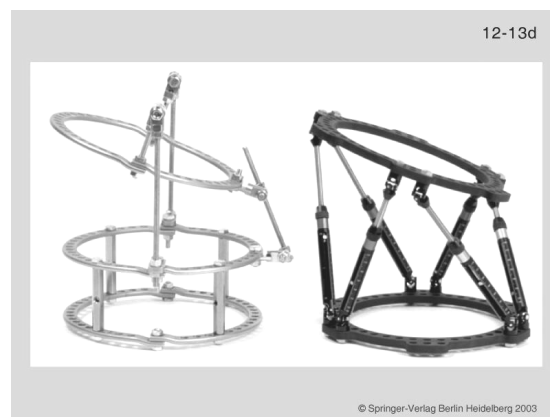


Fig. 17b: Ilizarov angulation-translation device

The TSF is a very strong construct. When compared with the Ilizarov fixator, the Spatial Frame was 1.1 times as axially stiff, was 2.0 times as stiff in bending, and had 2.3 times the torsional stiffness ³⁹.

3.2.2 Surgical Technique

During surgery, the proper ring diameter and type (full or two-third) are chosen for the proximal and distal ring. Differently sized rings may be used for the same frame to achieve the most comfortable profile of the frame. Each full ring carries six tabs; the Master Tab is always located at the proximal ring, regardless of the type of referencing applied. The standard orientation of the master tab is always anterior, strut 1 and 2 are connected there. Different rotational orientations, especially for the femoral frame, can be used by changing the rotary frame offset.

Tensioned wires with a diameter of 1.8 mm and half pins with a diameter of 5 or 6 mm are used as a hybrid method for the fixation of the rings at the bone. The anatomic topography has to be respected to avoid injury to nerves and vessels. At each level of the limb special fixation techniques are described. At the distal femur one horizontal reference wire and one posteromedial and one posterolateral half-pin are inserted ⁷. An orthogonal reference ring placement is strongly recommended, both in the frontal and sagittal plane.

Six struts with appropriate length connect the two rings.

The ring type and size and the type and length of the struts characterize the frame parameters in the software program.

After determination of the mounting parameters the percutaneous osteotomy is performed by using the drill-hole-method or the Gigli-saw-method.

3.2.3 Reference Fragment and Moving Fragment

Orthopedic convention characterizes the deformity of the distal fragment with respect to the proximal fragment (The proximal fragment is the reference fragment; the distal fragment is the moving fragment) ⁴⁸.

Using the TSF, both the proximal and the distal fragment can act as the reference fragment. Distal referencing is especially useful in distal malunions with a short distal fragment. In this case intraoperatively the attachment of the distal reference ring can be performed more exactly in an orthogonal position. Here the reference ring is close to the joint line, which acts as a landmark.

Ideally, the reference fragment should fulfill two criteria: first, its anatomic planes should closely match the planes of the AP and lateral radiographs; second, AP and lateral radiographs should include the level of attachment of the reference ring to the reference fragment.

Therefore, a proximal reference fragment is preferred for proximal tibial deformities, whereas a distal reference fragment is preferred for distal femoral and distal tibial deformities.

3.2.4 Origin and Corresponding Point

After determination of the reference and the moving fragment, the Origin and the Corresponding Point have to be defined.

By definition Origin and Corresponding Point coincide after correction has finished.

The Origin may be chosen at any point along the reference fragment axis, as long as its Corresponding Point can be identified at the axis of the moving fragment.

The CORA is a good choice for the Origin in many cases, especially in chronic deformities. Here, bone ends are not identifiable like in acute fracture cases.

The Origin works as a virtual hinge, angular corrections are performed around this point. It is essential that the position of the Origin can be accurately determined on both AP and lateral radiographs ⁵².


In deformities with significant malrotation it is especially important to place the Origin in the center of the bone at the level of the osteotomy. With it, no additional translation deformity is created by rotation around this center.

For neutral wedge corrections, the Origin is placed on the anatomic axis, for open wedge corrections it is placed on the convex cortex.

3.2.5 The Software: Frame, Deformity and Mounting Parameters

To correct a specific deformity with the TSF, several parameters have to be inserted in the web-based software.

Frame parameters: The type and size of the rings and the type of the struts have to be entered (Fig. 18).

TAYLOR SPATIAL FRAME* 

Home Cases Utilities Literature User Profile Logout Help

File Case Info Define Deformity **Select Frame** Mount Frame Initial Frame Final Frame Structure at Risk Prescription Report

Case Name: GEA HTO Surgery
8/12/02

Ring Selection: ?

Proximal Ring*: 180 mm, 7107-0115 2/3 Ring/U-Plate Orientation: Select

Distal Ring: 180 mm, 7107-0115 Select

* Reference Ring

Strut Family:

☐ Standard Struts ☐ Fast Fx ☒ Use Selection Below

Strut Selection:

	Standard Struts				Fast Fx <input checked="" type="radio"/>			
Size:	Extra Short	Short	Medium	Long	Extra Short	Short	Medium	Long
Range:	75-96 mm	90-125 mm	116-178 mm	169-283 mm	91-121mm	116-152 mm	143-205 mm	195-311 mm
Cat. No.:	7107-0205	7107-0210	7107-0220	7107-0230	7107-0705	7107-0710	7107-0720	7107-0730
	Select All	Select All	Select All	Select All	Select All	Select All	Select All	Select All
Strut 1 <input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Strut 2 <input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Strut 3 <input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Strut 4 <input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Strut 5 <input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Strut 6 <input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

TSF Web Application Version 2.1.0
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Fig. 18: TSF-software: Select Frame Site

Deformity Parameters: All deformity parameter measurements are made relative to the reference fragment; the Origin and the Corresponding Point have to be chosen. A thorough analysis of AP and lateral radiographs and a clinical examination to determine malrotation are required.

A deformity between two bone segments is characterized by three projected angles (rotations) and three projected displacements (translations).

Therefore, a total of six deformity parameters are required to describe a single deformity: (1) AP view angulation, varus or valgus; (2) lateral view angulation, procurvatum or recurvatum; (3) axial view angulation, external or internal rotation; (4) AP view translation, medial or lateral; (5) lateral view translation, anterior or posterior; (6) axial view translation, short or long (Fig. 19).

External or internal rotation is measured by clinical examination or CT-scan. The other parameters are measured from AP and lateral radiographs.

TAYLOR SPATIAL FRAME* smith&nephew

Home Cases Utilities Literature User Profile Logout Help

File Case Info Define Deformity Select Frame Mount Frame Initial Frame Final Frame Structure at Risk Prescription Report

Reference Fragment: Proximal Case Name: GEA HTO Surgery 8/12/02

AP View Angulation (deg) 23.0 <input type="radio"/> Valgus <input checked="" type="radio"/> Varus	Lateral View Angulation (deg) 10.0 <input type="radio"/> Apex Posterior <input checked="" type="radio"/> Apex Anterior	Axial View Angulation (deg) 15.0 <input type="radio"/> External <input checked="" type="radio"/> Internal
AP View Translation (mm) 10.0 <input checked="" type="radio"/> Medial <input type="radio"/> Lateral	Lateral View Translation (mm) 5.0 <input type="radio"/> Anterior <input checked="" type="radio"/> Posterior	Axial Translation (mm) 5.0 <input checked="" type="radio"/> Short <input type="radio"/> Long

Right AP View Right Lateral View Right Axial View

Lateral Medial Posterior Anterior Medial Lateral

Clicking on graphic will enlarge ? Previous Regenerate Views Next

TSF Web Application Version 2.1.0
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Fig. 19: TSF-software: Define Deformity Site

Mounting parameters: The mounting parameters characterize the position of the reference ring (proximal or distal) on the limb with respect to the position of the origin, which acts as a virtual hinge. That means, the mounting parameters determine the position of the center of the reference ring to the position of the Origin ³⁹.

Four parameters have to be inserted: (1) AP view frame offset, medial or lateral offset of the center of the reference ring to the Origin; (2) lateral view frame offset, anterior or posterior offset; (3) axial frame offset, proximal or distal offset of the reference ring; (4) rotary frame offset, the degree of rotation between the master tab and the designated AP plane (Fig. 20).

Mostly the frame is placed in a neutral position without a rotational offset. In the distal femur, an external rotational offset of 60 degrees allows a better position for patient's comfort.

TAYLOR SPATIAL FRAME* 

Home Cases Utilities **Mount Frame** Initial Frame Final Frame Structure at Risk Prescription Report

Operative Mode ? Case Name: GEA HTO Surgery 8/12/02

☐ Total Residual ☐ Chronic ☐ Residual

Mounting Parameters

AP View Frame Offset (mm) Lateral View Frame Offset (mm) Axial Frame Offset (mm)


☐ Medial to Origin ☐ Anterior to Origin ☒ Proximal to Origin

☐ Lateral to Origin ☐ Posterior to Origin ☐ Distal to Origin

Rotary Frame Angle (deg)


☐ Frame Externally Rotated ☐ Frame Internally Rotated ?

Right AP View ?



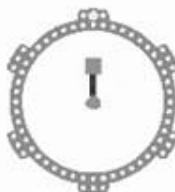
Lateral Medial

Right Lateral View ?



Posterior Anterior

Right Axial View



Medial Lateral

Clicking on graphic will enlarge ?

TSF Web Application Version 2.1.0
Taylor Spatial Frame™ property of [Smith & Nephew](#).

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Fig. 20: TSF-software: Mount Frame Site

There are some more obligatory sites in the software program:

The Initial Frame Site shows the frame position and deformity on day one of the prescription schedule. In the Total Residual Mode the initial strut length has to be inserted.

The Final Frame Site displays the frame position and the corrected deformity on the last day of strut adjustment. In the Total Residual Mode, most if not all struts, will have different values on the screen.

The Structure At Risk (SAR) Site is used to set up the time it will take to correct the deformity. Entering SAR-values will reduce the velocity of correction.

At the Prescription Site the start date can be modified. Colored fields clearly identify when struts need to be changed to a different size.

The Report Site provides a summary of all the input and output information. A printed version of the report site should be handed over to the patient.

3.2.6 Modes of Correction

At the moment, three program modes of correction can be utilized with the TSF: Chronic deformity mode, residual deformity mode and total residual deformity mode. Since the introduction of the Total Residual Method, the other ones have been used less frequently.

3.2.6.1 Chronic Deformity Method

In the chronic mode, radiographic measurements are used in conjunction with the computer software to provide six strut settings that cause the TSF to mimic the deformity (Fig. 21a). The reference ring is then attached to the patient, the mounting parameters can be measured, and after that the second ring can be mounted. The patient then adjusts the struts back to their neutral position based on a daily prescription schedule for strut adjustment. The software calculates this prescription. The final frame position is characterized by the same length of all struts and a parallel position of both rings (Fig. 21b). Ideally the deformity is fully corrected. If there is still some deformity when the rings have become parallel, another correction method can be applied.



Fig 21a: The frame mimics the deformity.

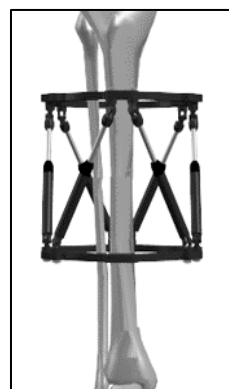


Fig. 21b: The deformity is corrected, the struts are in their neutral length.

3.2.6.2 Residual Deformity Method

This method is used in any situation with a neutral TSF attached to persistent bone deformity prior to strut length calculation (Fig. 22a). After insertion of the deformity and mounting parameters, the prescription for strut adjustment is calculated by the software. The frame is adjusted from its neutral to an oblique position to correct the skeletal deformity (Fig. 22b).

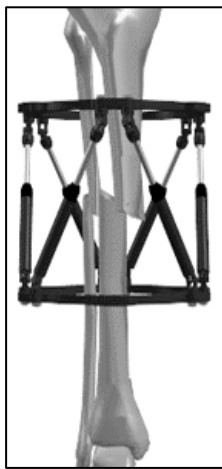


Fig. 22a: The frame is attached in neutral position.

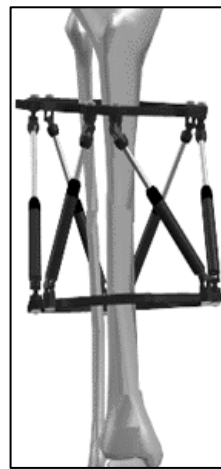


Fig. 22b: After correction, the frame is in an oblique position.

3.2.6.3 Total Residual Deformity Method

Since its advent in 2003, this mode is mostly used for deformity correction. It can be described as the “crooked frame on crooked bone”. All struts can have unequal length (Fig. 23a). With this mode, the moving ring can be attached without any intraoperative strut length calculations by the software in the best centralized position. This might be the greatest advance on the chronic mode.

After the frame is attached, the software parameters can be determined, including the initial length of each strut. The software will calculate the final strut length to correct the deformity (Fig. 23b).

For the total residual deformity mode, the rings are applied independently of each other. Nevertheless, it is strongly recommended to mount the reference ring perpendicular to the long axis of the reference bone segment, both in AP and lateral view. Orthogonal reference ring placement facilitates planning by making the mounting parameter reference lines parallel to the reference bone axis line ³⁹.



Fig 23a: Crooked frame on crooked bone.



Fig. 23b: Crooked frame on corrected bone.

3.2.7 Planning Methods

JC Taylor, JE Herzenberg, D Paley and SC Standard developed different planning methods for deformity correction using the Taylor Spatial Frame ³⁹.

3.2.7.1 Fracture Method

With the fracture method, the Origin and Corresponding Point are chosen as congruent points on opposite sides of a fracture. After correction, these two points will coincide at the same location.

It is a preferred method to use the end of a recognizable spike on the reference fragment as the Origin; the corresponding negative of the spike on the moving fragment is used as the Corresponding Point (Fig. 24).

The deformity parameters are measured by calculating the angulations and translations in both planes, the rotation deformity is measured by clinical examination or CT-scan. The mounting parameters are determined, the initial strut length is inserted in the total residual program, and the software will generate the daily prescription schedule for strut adjustment and deformity correction.

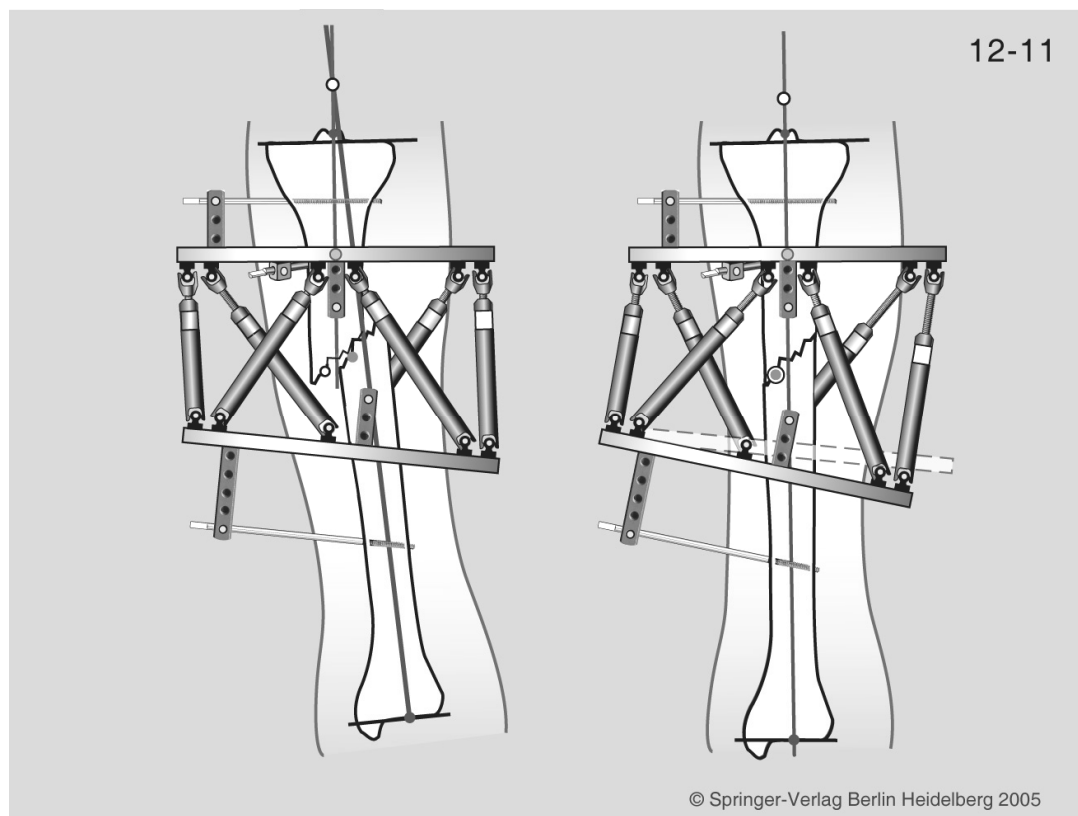


Fig. 24: Fracture Method: Origin and Corresponding Point coincide after deformity correction.

3.2.7.2 CORAgin Method

In the case of chronic deformities without identifiable corresponding bone ends, the fracture method cannot be used. Such deformities include various congenital, posttraumatic and hereditary diseases.

With the CORAgin method, the Origin is chosen to be the CORA, and the Corresponding Point is determined by using local length analysis or by adding a certain amount of length in case of leg length discrepancy³⁹.

Local length analysis (Fig. 25) is used when the planned correction is a pure neutral wedge. This analysis allows calculation of the amount of the existent shortening due to the deformity. The amount is added to determine the position of the Corresponding Point.

An alternative way for determining the Corresponding Point is by adding a certain amount of length needed during deformity correction. This amount is added on the moving segment axis line in a direction toward the reference fragment (Fig. 26).

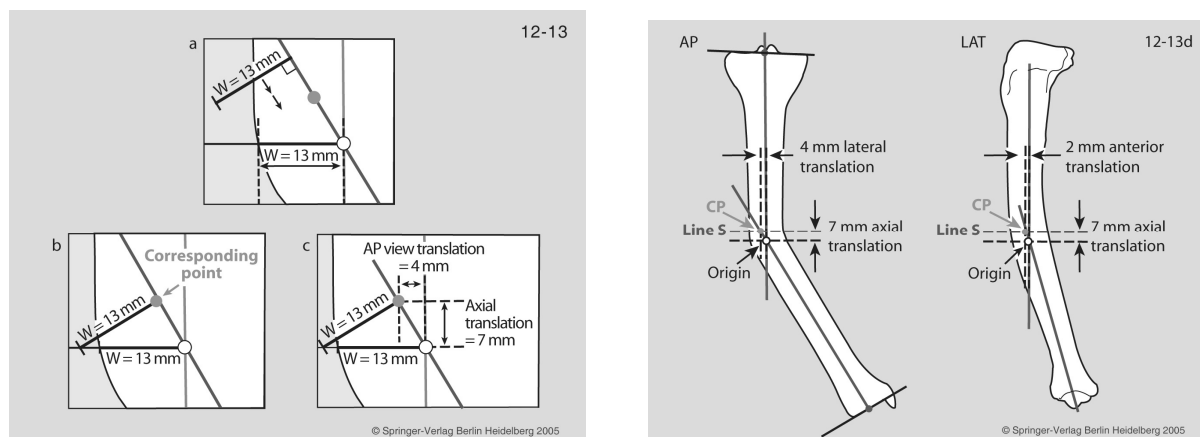


Fig. 25: CORAgin Method: Local length analysis.

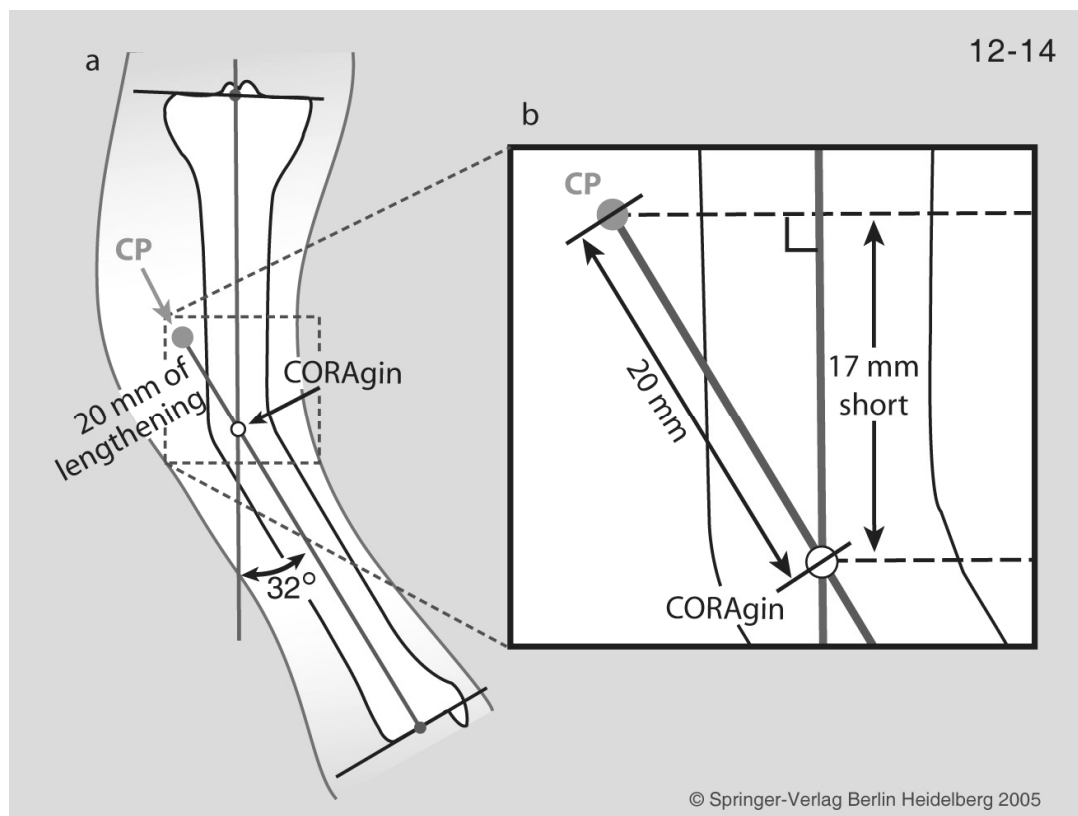


Fig. 26: CORAgin Method: Adding the amount of 20 mm of length

3.2.7.3 CORAsponding Point Method

With this method, the Corresponding Point is chosen first and is determined to be at the CORA instead of the Origin. This places the Corresponding Point on the reference line. The CORAsponding Point method is especially helpful when extrinsic length has to be added. The length is added on the reference line by moving the Origin along the reference line toward the moving fragment. This new point is called the Extrinsic Origin³⁹.

The advantage of this method is that it eliminates secondary translation deformities in the AP and lateral plane due the lengthening process. One disadvantage is that it increases the value of the axial frame offset, this may be a cause for measurement errors.

The mounting parameters are based on the position of the Extrinsic Origin relative to the center of the reference ring (Fig. 27).

After insertion of all data to the software, the computer creates the correction schedule.

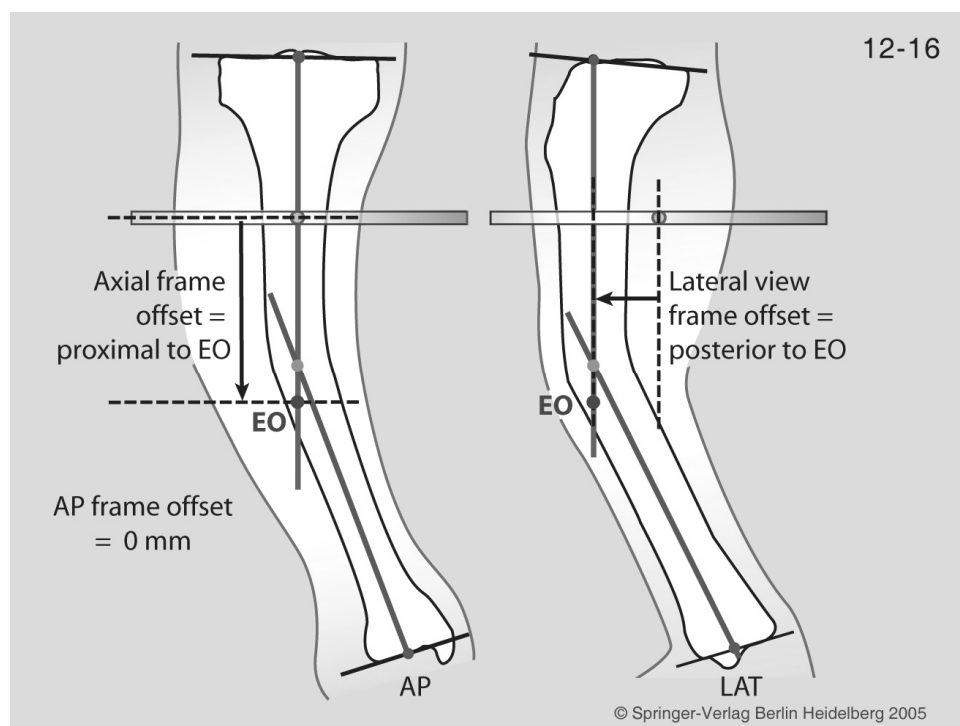


Fig. 27: CORAsponding Point Method: Determination of the Extrinsic Origin, the mounting parameters characterize the position of the reference ring with respect to the position of the Extrinsic Origin.

3.2.7.4 Virtual Hinge Method

With this method, the Origin and the Corresponding Point are placed at the same point in space, ideally at the CORA. A virtual hinge is created for rotational corrections. It can be used for opening wedge osteotomies when placed on the transverse bisector line at the convex surface of the bone (Fig. 28).

The virtual hinge can be chosen also outside at the transverse bisector line, and then additional length can be gained. When adding length with this method, the planning becomes the CORAgin method ³⁹.

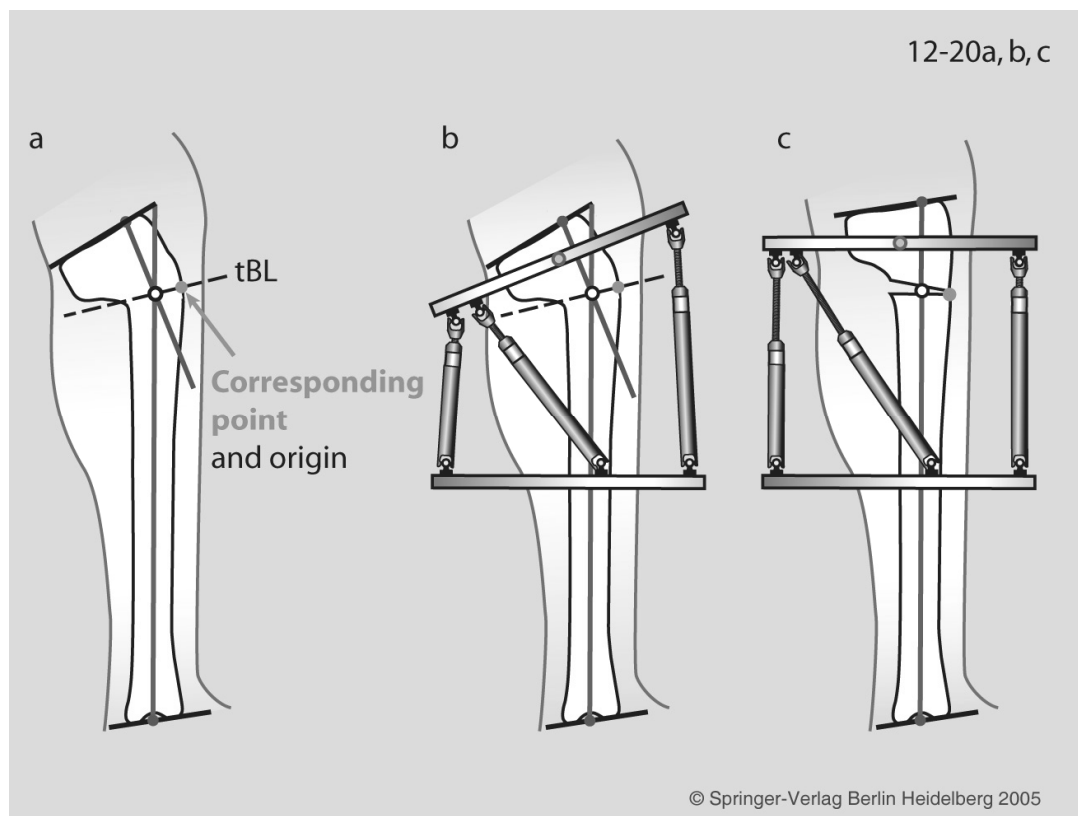


Fig. 28: Virtual Hinge Method: Origin and Corresponding Point on the transverse bisector line at the convex surface of the bone: open wedge osteotomy.

Summarizing the Taylor Spatial Frame is widely accepted in the treatment of fractures, non-unions and malunions due to different reasons^{13,14,38,49,50}; successful anatomic or nearly anatomic restoration of alignment is reported³². One of its biggest advantages is the option to perform a second residual correction program without changing hinges or reoperation, when the initial program did not result in perfect alignment.

3.3 Patients and Method

We retrospectively analyzed our prospective database of patients being treated with external fixation using the Taylor Spatial Frame which was started in June 1999. We included all patients in whom correction and limb lengthening was performed with the TSF.

Patients treated with other external fixation devices, with internal lengthening nails, or acute corrections followed by plating were excluded. Additionally we excluded patients, in which the TSF was used for an arthrodesis at the knee or ankle joint. The remaining patients were analyzed in respect to the mode of correction, the location of the osteotomy and the indication for treatment. The demographic data, the age at operation and the time in frame were calculated.

Patients with posttraumatic malalignment and shortening, and patients with congenital femoral deficiency were analyzed separately. In these more demanding patient groups we additionally analyzed the external fixation index and the radiological and clinical outcome and described problems, obstacles and complications of treatment.

Between June 1999 and February 2009 a total of 320 patients were treated with 501 Taylor Spatial Frames. The correction was performed at the distal femur in 135 cases, at the proximal tibia in 254 cases, at the distal tibia in 22 cases, and as a bi-level correction with two frames on one tibia in 45 cases (90 frames). Eleven cases with arthrodeses of the knee or ankle joint were excluded.

This left 309 patients with 490 cases for further analysis (distal femur 135 cases, proximal tibia 251 cases, distal tibia 14 cases, bi-level tibia 45 cases (90 frames). There were 150 females and 160 males. The average age at operation was 17.52 years (2.86 to 72.35 years), the average duration of external fixation was 5.99 month (0.90 to 17.87 month).

In 70 cases the chronic deformity mode was used while 420 cases were corrected with the total residual mode.

Subgroups were defined, allowing analysis according to the different aetiologies. The diagnosis of Congenital Femoral Deficiency (CFD) was present in 38 patients, Fibular Hemimelia or Fibular Aplasia (FH/FA) in 44 patients, posttraumatic deformities (PT) in 63 patients, postinfectious deformities (PI) in 10 patients, hereditary deformities due to different syndromes (HER) in 112 patients, idiopathic deformities (IDIO) in 34 patients, and Congenital Pseudarthrosis of the Tibia (CPT) in 8 patients.

Patients suffering both from congenital femoral deficiency and fibular hemimelia were counted with their main diagnosis (Fig. 29).

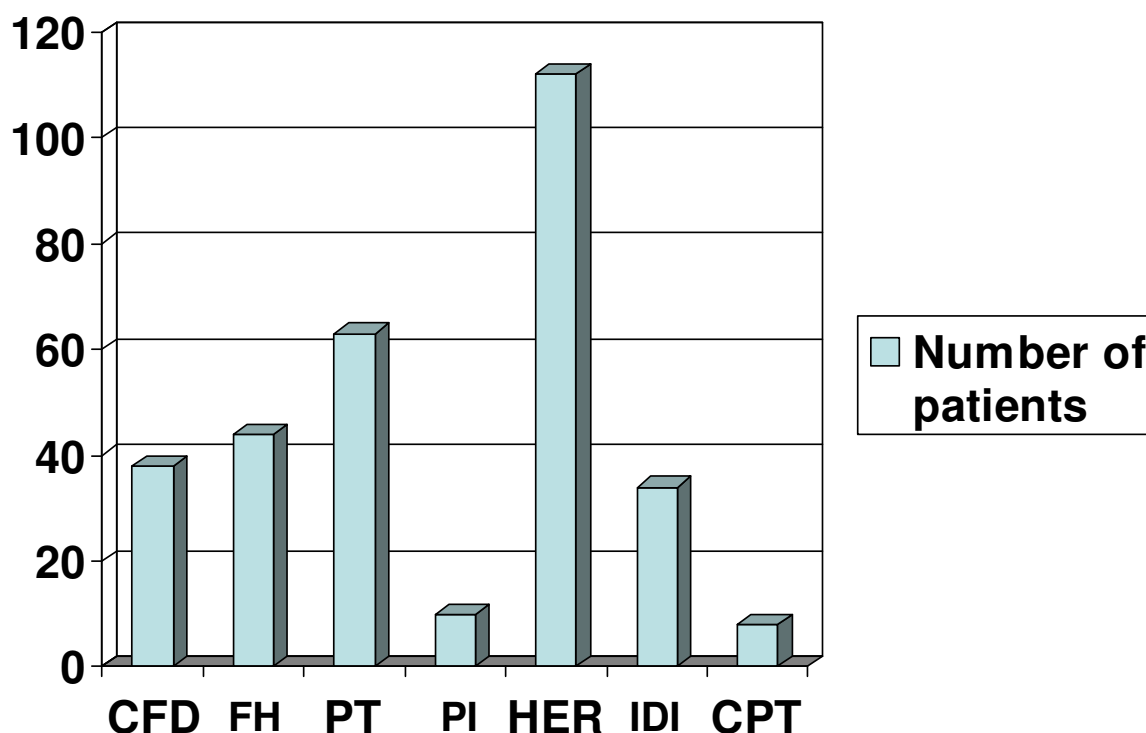


Fig. 29: Subgroups of patients of the complete TSF-database

Two subgroups were analyzed separately and more in detail. Additionally the external fixation index, the radiological and clinical outcome and complications of the procedure were described.

A study of posttraumatic patients was performed in 2005 including 22 patients with 25 corrections, operated between 2000 and 2004 with a minimum follow-up of 6 month. The deformities were classified into three groups according to the affected bone and the osteotomy level. 9 deformities located in the femur formed group 1. Group 2 consisted of 9 proximal tibial deformities and group 3 consisted of 7 distal tibial deformities.

Another study was performed in 2008 reviewing 31 patients with 35 operative procedures between 1998 and 2007 suffering from Congenital Femoral Deficiency (CFD). The radiological and clinical outcome was assessed. Problems, obstacles and complications were described in detail; solutions were presented to avoid them.

4 Results

Results of the complete TSF-database:

From the 309 patients with 490 TSF-cases 7 subgroups were analyzed (Fig. 30):

Group 1: Congenital Femoral Deficiency (CFD): Thirty-eight patients with 49 frames could be evaluated. Several patients had repeated surgeries because of recurrence of leg length difference or deformity during growth. There were 16 females and 22 males. The average age at operation was 10.83 years (3.45 to 41.03 years); two patients were in the age-group over 20 years. The average duration of external fixation was 6.21 months (2.63 to 9.57 months).

Group 2: Fibular Hemimelia and Fibular Aplasia (FH/FA): Forty-four patients with 78 frames were found. In this group patients had single or bi-level osteotomies and bilateral or repeated surgeries. There were 16 females and 28 males. The average age at operation was 9.98 years (2.86 to 24.91 years); the average duration of external fixation was 5.63 months (1.63 to 10.57 months).

Group 3: Posttraumatic deformities (PT): Sixty-three patients with 85 frames could be analyzed. There were 25 females and 38 males. Thirty-two frames were performed at the distal femur, 34 at the proximal tibia, 7 at the distal tibia, and 6 as bi-level cases (12 frames). The average age at operation was 26.20 years (6.66 to 61.68 years); the average duration of external fixation was 6.81 months (0.90 to 14.73 months). In this group a lot of adults could be found, sometimes with delayed callus formation.

Group 4: Postinfectious deformities (PI): Ten patients with 19 frames could be evaluated. There were 4 females and 6 males. Eight frames were performed at the distal femur, 9 at the proximal tibia, and one as a bi-level case (2 frames). The average age at operation was 22.12 years (8.12 to 45.89 years); the average duration of external fixation was 7.73 months (4.20 to 9.70 months).

Group 5: Hereditary deformities (HER): Different syndromes and aetiologies were summarized in this group. One hundred-twelve patients with 198 frames could be evaluated. There were 67 females and 45 males. Forty-four frames were performed at the distal femur, 109 at the proximal tibia, 5 at the distal tibia, and 20 as bi-level cases (40 frames). The average age at operation was 15.86 years (3.68 to 65.16 years); the lady at age 65 suffered from Paget disease. The average duration of external fixation was 5.83 months (2.20 to 17.87 months).

Group 6: Idiopathic deformities (IDIO): Thirty-four patients with 49 frames could be evaluated. There were 16 females and 18 males. Eleven frames were performed at the distal femur, 32 at the proximal tibia, 2 at the distal tibia, and 2 as bi-level cases (4 frames). The average age at operation was 24.24 years (7.50 to 72.35 years); the lady at age 72 was corrected because of severe valgus deformity before total knee arthroplasty. The average duration of external fixation was 5.44 months (3.07 to 11.77 months).

Group 7: Congenital Pseudarthrosis of the Tibia (CPT): Eight patients with 12 frames could be evaluated. There were 5 females and 3 males. Three frames were performed at the proximal tibia, one at the distal tibia, and 4 as bi-level cases (8 frames). The average age at operation was 19.57 years (3.79 to 53.45 years); the average duration of external fixation was 7.32 months (3.03 to 9.83 months).

	Patients	Frames	Mean age at operation (years)	Duration of external fixation (month)
CFD	38	49	10.83 (3.45 - 41.03)	6.21 (2.63 - 9.57)
FH/FA	44	78	9.98 (2.86 - 24.91)	5.63 (1.63 - 10.57)
PT	63	85	26.20 (6.66 – 61.68)	6.81 (0.90 – 14.73)
PI	10	19	22.12 (8.12 – 45.89)	7.73 (4.20 – 9.70)
HER	112	198	15.86 (3.68 – 65.16)	5.83 (2.20 – 17.87)
IDIO	34	49	24.24 (7.50 – 72.35)	5.44 (3.07 – 11.77)
CPT	8	12	19.57 (3.79 – 53.45)	7.32 (3.03 – 9.83)
Total:	309	490		

Fig. 30: Number of patients and frames, mean age of operation and duration of external fixation

4.1 Accuracy of the TSF in comparison with the Ilizarov fixator (IRF)

As mentioned before, the bending and torsional stiffness of the TSF is twice as high as the Ilizarov fixator. The computational accuracy of the computer program is 1/1,000,000 inch and 1/10,000°. The real mechanical accuracy, using manual adjustment of the struts for even a full six-axis deformity correction, has been measured to within 0.7° and 2 mm³⁹.

In 2005 a study was performed at the Orthopaedic Hospital Vienna-Speising to compare the accuracy of deformity correction in the lower limb between the TSF and the Ilizarov ringfixator (IRF).

This study was published in 2007 by Manner, Hübl et al.³².

The goal was to compare the final result after frame removal with the initial aim of deformity correction and lengthening, therewith the accuracy of both methods could be checked.

Patients and methods: In a retrospective review, a total of 278 consecutive lower-limb deformity corrections in 207 patients operated either with the TSF or IRF between January 1985 and December 2004, were evaluated.

The inclusion criterion was the use of the TSF or the IRF for any gradual deformity correction in the lower-limb.

Incomplete medical reports and X-rays, acute deformity corrections and complications, which were not fixator-related, were rated as exclusion criteria.

After application of those criteria 208 gradual deformity corrections in 155 patients were included in this study.

The IRF was used in 79 cases; the TSF was used in 129 cases. The mean age at the time of operation was 13.2 years (range 2-49 years).

Femoral corrections were performed in 58 cases; tibial corrections in 150 cases.

The indication was congenital in 85 cases, posttraumatic and postinfectious in 44 cases, hereditary in 53 cases and idiopathic in 26 cases.

For evaluation of the preoperative deformity and the final result we used AP and lateral long leg standing X-rays and orthoradiograms. A CT-scan was used in cases with rotational deformity. The method according to Paley was applied for deformity analysis ⁴¹.

For evaluation of the result, the final result was compared with the initial aim of deformity correction to assess the accuracy of both methods.

Specification of the type of deformity correction: Four types of deformity correction were specified:

Type I: (one-dimensional deformity correction, 1D): all cases with leg lengthening only, without any axial correction.

Type II: (two-dimensional deformity correction): all cases with leg lengthening and additional axial correction in one plane (frontal, sagittal, rotational).

Type III: (three-dimensional deformity correction): all cases with leg lengthening and additional axial correction in two planes (frontal, sagittal, rotational).

Type IV: (four-dimensional deformity correction): all cases with leg lengthening and additional axial correction in three planes (frontal, sagittal, rotational).

Persisting deformity after frame removal: For evaluation of the accuracy of deformity correction the results were graded in four groups immediately after frame removal:

Group I: all cases without any persisting deformity after correction.

Group II: all cases with a minor persistent deformity ($< 5^\circ$).

Group III: all cases with a moderate persistent deformity ($6-10^\circ$).

Group IV: all cases with a severe persistent deformity ($>10^\circ$).

Results:

The preoperatively defined aim of deformity correction is illustrated in Fig. 31.

Aim of correction	IRF		TSF	
	n	Mean	n	Mean
Lengthening	79	4.9 cm	129	2.7 cm
Frontal plane	43	14.5°	108	11.3°
Sagittal plane	21	24.5°	23	13.4°
Rotational plane	2	15.0°	47	16.4°

Fig. 31: Preoperatively defined aim of deformity correction in the IRF and TSF group.

Dimensions of gradual deformity corrections:

Leg lengthening procedures (Type I) were performed in a significantly ($P < 0.05$) higher percentage in the IRF-group (36.7%) than in the TSF-group (10.9%).

The majority of cases consisted of Type II corrections with comparable percentages in both groups (IRF: 44.3%; TSF: 47.2%).

In the group of Type III corrections, a significantly ($P < 0.05$) higher percentage of cases was treated with the TSF (34.9%) than with the IRF (17.7%).

In the group of Type IV corrections, again a significantly ($P < 0.05$) higher percentage was treated with the TSF (7.0%) than with the IRF (1.3%), (Fig. 32).

Type of correction	IRF		TSF	
	n	%	n	%
Type I	29	36.7	14	10.9
Type II	35	44.3	61	47.2
Type III	14	17.7	45	34.9
Type IV	1	1.3	9	7.0
All	79	100.0	129	100.0

Fig. 32: Distribution of dimensions of deformity correction in the IRF and TSF group.

Persistent axial deformity in the IRF and TSF group:

Of the 79 cases treated with the IRF, there was no residual deformity in 44 cases (55.7%). In the remaining 35 cases (44.3%) a persistent deformity was evident after frame removal. A minor deformity ($<5^{\circ}$) was evident in 11 cases (13.9%), a moderate deformity ($6-10^{\circ}$) was evident in 16 cases (20.3%), and a severe deformity ($>10^{\circ}$) was present in 8 cases (10.1%).

Of the 129 cases treated with TSF, there was no residual deformity in 117 cases (90.7%). In the remaining 12 cases (9.3%) a persistent deformity could be measured after frame removal. A minor deformity was evident in 7 cases (5.4%), a moderate deformity in 1 case (0.8%), and a severe persisting deformity was present in 4 cases (3.1%), (Fig. 33).

Persistent deformity	IRF		TSF	
	n	%	n	%
No deformity	44	55.7	117	90.7
Minor	11	13.9	7	5.4
Moderate	16	20.3	1	0.8
Severe	8	10.1	4	3.1

Fig. 33: Persistent deformity after frame removal in the IRF and TSF group.

Persistent axial deformity in connection with the dimensionality of the deformity correction:

In both groups, one essential finding was obvious. With rising dimensions of axial corrections, an increasing percentage of residual deformities could be seen.

The goal of treatment in Type I - corrections was achieved in 79.3% of the IRF-cases and in 100% of the TSF-cases ($P < 0.05$).

The goal of treatment in Type II - corrections was achieved in 48.6% of the IRF-cases and in 91.8% of the TSF-cases ($P < 0.05$).

The goal of treatment in Type III - corrections was achieved in 28.6% of the IRF-cases and in 91.1% of the TSF-cases ($P < 0.05$).

The goal of treatment in Type IV - corrections was not achieved in the single IRF-case, but it was achieved in 66.7% of the TSF-cases, (Fig. 34).

Correction of deformity and dimensionality	IRF	TSF
	%	%
Type I (1D-correction)	79.3	100
Type II (2D-correction)	48.6	91.8
Type III (3D-correction)	28.6	91.1
Type IV (4D-correction)	0	66.7

Fig. 34: Correction of deformity after frame removal in connection with the dimensionality in the IRF and TSF group.

In conclusion the accuracy-study showed clear advantages of the TSF compared to the Ilizarov ringfixator. Especially in complex multiplanar deformities the TSF allowed much higher precision, whereas treatment with the Ilizarov fixator in multidimensional deformities more often resulted in residual malalignment³².

The potential of simultaneous six-axis correction in complex deformities is an enormous advantage of the TSF-system.

4.2 Results of Posttraumatic Deformity Correction in the Lower Extremity using the TSF

A subgroup analysis reviewing posttraumatic patients was performed by B. Speigner in 2005 as part of a student's master thesis under the supervision of the author of this study⁵², the results were published in 2009¹⁷.

The aim of the study was to evaluate the results of treatment at the Orthopaedic Hospital Vienna-Speising in patients suffering from posttraumatic deformities at the lower extremities using the Taylor Spatial Frame (TSF).

Patients and methods: In the period from February 2000 to January 2004, 22 patients were included in this consecutive retrospective clinical and radiological study.

As inclusion criteria all patients with posttraumatic deformities were rated, who had operative treatment with gradual correction using the TSF in the mentioned time period. To take part in this study the frame had to be removed before June 2004.

The exclusion criterion was the use of internal fixation techniques with acute correction and the use of other fixator types.

11 female and 11 male patients underwent deformity correction. The mean age of the patients at the occurrence of trauma was 14.3 years (2 to 46 years). The mean age at the time of correction was 22.7 years (12 to 48 years). The mean period between occurrence of trauma and deformity correction was 8.2 years (0.5 to 27 years). The mean duration of follow up was 21.1 months (12 to 43 months).

All deformities were classified as posttraumatic. In 18 patients the fracture occurred before growth plate closure, with the result of partial or complete growth arrest with deformity and leg length discrepancy. In 4 patients the fracture happened after physeal closure ending with malalignment at the fracture site.

A total of 24 limb segments (9 femurs, 15 tibias) in 22 Patients were treated for lengthening, mostly with simultaneous gradual deformity correction because of their concomitant axial or rotational deformity.

The deformities were classified into three groups according to the affected bone and the osteotomy level. 9 deformities located in the femur formed group 1.

Group 2 consisted of 9 proximal tibial deformities and group 3 consisted of 7 distal tibial deformities. One bi-level tibia lengthening was split in two separate cases.

A total of 25 lengthening and correction procedures were studied.

For preoperative planning and final assessment long standing AP radiographs in patella forward position, lateral views, orthoradiograms and standing pelvic radiographs were performed. CT-scans were used in case of rotational deformities.

Surgical technique: All frames were fixed in a typical hybrid technique with wires and half-pins. The osteotomy was done percutaneously after pre-drilling. As the mode of correction in the software program, the Chronic Deformity Method was used until the end of 2002, after that the Total Residual Deformity Method was used exclusively for lengthening and deformity correction. After consolidation of the distraction gap the frame was removed.

Evaluation: To assess the outcome and the accuracy of treatment, radiographs were evaluated preoperatively, after gradual correction, after frame removal and at the follow-up examination.

The method according to Paley was applied for deformity analysis ⁴¹.

The important angles for group 1 (distal femur) were the mLDFA in the frontal plane and the PDFA in the sagittal plane. In group 2 (proximal tibia) the MPTA was measured in the frontal plane and the PPTA in the sagittal plane. In group 3 (distal tibia) the LDFA was measured in the frontal plane and the ADFA in the sagittal plane. The MAD was determined in group 1 and 2.

The mean duration of external fixation (time from application to removal of the frame) and the external fixation index (number of months of external fixation per centimetre of lengthening) were calculated in all patients.

The range of motion of the adjacent joint was evaluated clinically preoperatively, during time in frame, after frame removal and at the last follow-up examination.

Problems, obstacles and complications were assessed according to the classification of Paley ⁴⁰.

Results:

Group 1 (distal femur): This group consisted of 9 cases, 6 valgus- and 3 varus deformities were treated, additionally one flexion- and one rotational deformity was corrected.

The mean mLDFA preoperatively was $84.4^{\circ} \pm 9.8^{\circ}$ (64° to 100°); it was outside normal range in all cases. The mean mLDFA postoperatively was $88.3^{\circ} \pm 1.5^{\circ}$ (85° to 90°). The mean difference between the pre- and postoperative mLDFA was $8.11^{\circ} \pm 7.0^{\circ}$ (2° to 26°).

The mean MAD preoperatively was $36.8 \text{ mm} \pm 18.3 \text{ mm}$ (10 to 80 mm); it was outside normal range in all cases. The mean MAD postoperatively was $7.1 \text{ mm} \pm 5.2 \text{ mm}$ (2 to 17 mm). The mean difference between the pre- and postoperative MAD was $31.7 \text{ mm} \pm 18.2 \text{ mm}$ (8 to 76 mm).

The mean amount of lengthening was $33.3 \text{ mm} \pm 15.6 \text{ mm}$ (15 to 62 mm).

The mean duration of external fixation was 5.8 ± 1.3 months (4 to 8.2 months). The mean external fixation index was 2.2 ± 1.0 months per centimetre (1.0 to 3.7 months per centimetre).

The mean preoperative knee flexion was 131° (90° to 150°). Three patients suffered from limitation preoperatively (one up to 90° , two up to 120°). During treatment, reduced flexion could be seen in all patients, 23% of preoperative flexion was possible at the end of the distraction period. After frame removal the flexion improved, at the six-month follow-up it was 90% of the preoperative value. The preoperative range of knee flexion was regained in all patients except one. In this patient the flexion decreased from 130° to 100° at the last follow-up.

Problems can be solved by definition by non-operative intervention before the end of treatment. 15 pin infections could be treated by antibiotics. Two residual deformities were corrected by additional programs.

Obstacles can be fully resolved by operative intervention before the end of treatment. One infected half-pin had to be removed due to recurrent infections.

Complications remain at the end of treatment. As a minor complication one scar excision was necessary for cosmetic reasons, one reduced knee flexion was observed (130° to 100°). As a true complication one femoral fracture happened after frame removal.

Group 2 (proximal tibia): This group consisted of 9 cases, lengthening was performed in all of them. 5 valgus-, 1 rotational- and 3 recurvatum deformities were treated. The mean magnitude of preoperative leg length difference was $23.4 \text{ mm} \pm 13.3 \text{ mm}$ (3 to 48 mm).

Preoperatively the MPTA was outside normal range (85° - 90°) in five cases. The mean value of these five cases was $92.4^\circ \pm 1.5^\circ$ (91° to 95°). The mean MPTA postoperatively was $88.6^\circ \pm 1.7^\circ$ (87° to 92°). The mean difference between the pre- and postoperative MPTA was $3.6^\circ \pm 1.0^\circ$ (2° to 5°). One patient still had a MPTA of 92° due to an undercorrection of a tibial valgus deformity (from 95° to 92°).

The mean MAD preoperatively of all cases was $14.7 \text{ mm} \pm 13.3 \text{ mm}$ (1 to 38 mm); it was outside normal range in 5 cases. The mean MAD postoperatively in all cases was $6.0 \text{ mm} \pm 4.4 \text{ mm}$ (0 to 17 mm). The mean difference between the pre- and postoperative MAD was $10.7 \text{ mm} \pm 8.7 \text{ mm}$ (1 to 35 mm). One patient still had a lateral displacement of the mechanical axis (from -38 mm to -17 mm) due to insufficient correction (MPTA 92°).

Preoperatively the PPTA was outside normal range (77° - 84°) in 4 cases. Three were treated because of recurvatum deformities. The mean preoperative PPTA of these 3 cases was $96.7^\circ \pm 5.3^\circ$ (90° to 103°). Postoperatively the mean PPTA was $82^\circ \pm 0.8^\circ$ (81° to 83°).

The mean amount of lengthening was $24.0 \text{ mm} \pm 12.0 \text{ mm}$ (7 to 52 mm).

The mean duration of external fixation was 6.0 ± 2.2 months (2.1 to 10.6 months).

The mean external fixation index was 3.0 ± 1.1 months per centimetre (1.4 to 4.7 months per centimetre).

The mean preoperative knee flexion was 144° (120° to 150°). In one patient flexion was possible only up to 120° . During treatment, the flexion was moderately reduced in all patients, 60% of preoperative flexion was possible at the end of the distraction period. After frame removal the flexion continued to improve in all cases, at the six-month follow-up it regained the preoperative value in all patients.

Eight pin infections occurred as a problem and were treated with antibiotics. Three residual deformities were corrected with additional programs.

Three pin infections were considered obstacles because of removal under anaesthesia.

Four complications occurred in this group. Three lesions of the deep peroneal nerve emerged during operation. Although the function was regained in all three cases, it is considered as a true complication, because it happened intraoperatively. One residual axial deviation (MPTA 92°) was present because of insufficient correction.

Group 3 (distal tibia): This group consists of 7 cases; all of them were treated with lengthening and axial correction. 5 varus-, 1 valgus- 1 rotational- and 1 extension deformities were corrected.

The mean magnitude of preoperative leg length difference was $25.8 \text{ mm} \pm 14.4 \text{ mm}$ (8 to 49 mm).

In 6 cases the LDTA was outside normal range (86°-92°). The mean preoperative value of these cases was $101^\circ \pm 13.1^\circ$ (80° to 120°). The mean LDTA postoperatively was $90.3^\circ \pm 2.9^\circ$ (84° to 93°). The mean difference between the pre- and postoperative LDTA was $14.3^\circ \pm 9.1^\circ$ (5° to 28°).

The mean amount of lengthening was $22.3 \text{ mm} \pm 13.1 \text{ mm}$ (3 to 44 mm).

The mean duration of external fixation was 6.2 ± 1.4 months (4.8 to 9.3 months). The mean external fixation index was 4.8 ± 4.7 months per centimetre (1.2 to 16 months per centimetre).

Five cases with an expected lengthening of more than 25 mm or an expected angular correction of more than 25° had an extension of the frame across the ankle to avoid equinus deformity during correction. This part was removed after the correction period.

The mean preoperative range of motion of the ankle joint was $61^\circ \pm 16^\circ$ (30° to 70°).

At the end of external fixation there was an average of 68% of the preoperative value. Five of the seven reached almost normal values 6 months after frame removal. In 2 patients a reduced dorsiflexion at the ankle joint in combination with mild osteoarthritis could be found preoperatively. Both had a long period between trauma and correction, both had a remarkable lengthening procedure at the distal tibia (36 mm, 44 mm). At the time of follow-up, the maximal dorsiflexion was 0° and 5° respectively. Radiograms showed aggravation of osteoarthritis.

Nine problems arose from pin infections and were treated with antibiotics. Four problems resulted from delayed ossification of the regenerate bone; cast treatment was performed after frame removal.

Three patients showed obstacles. Two screws had to be removed due to recurrent infections; one had screw renewal because of loosening during the distraction period. Two major complications were caused by functional limitation of the ankle joint due to osteoarthritis. One moderate frontal malalignment (LDTA 93°) was counted as a minor complication.

Amount of lengthening and external fixation index in all cases: The overall mean preoperative leg length discrepancy was $27.6 \text{ mm} \pm 14.7 \text{ mm}$ (3 mm to 61 mm). The mean amount of lengthening was $27.0 \text{ mm} \pm 14.8 \text{ mm}$ (3 mm to 62 mm). The mean duration of external fixation was 6.0 ± 1.7 months (2.1 to 10.6 months). The mean external fixation index of all corrections was 3.2 ± 2.9 months per centimeter (1.0 to 16 months per centimeter).

For lengthenings smaller than 30 mm the mean external fixation index was higher, and the variation of the index was larger than the index and the variation for lengthenings of 30 mm and more (Fig. 35, Fig. 36).

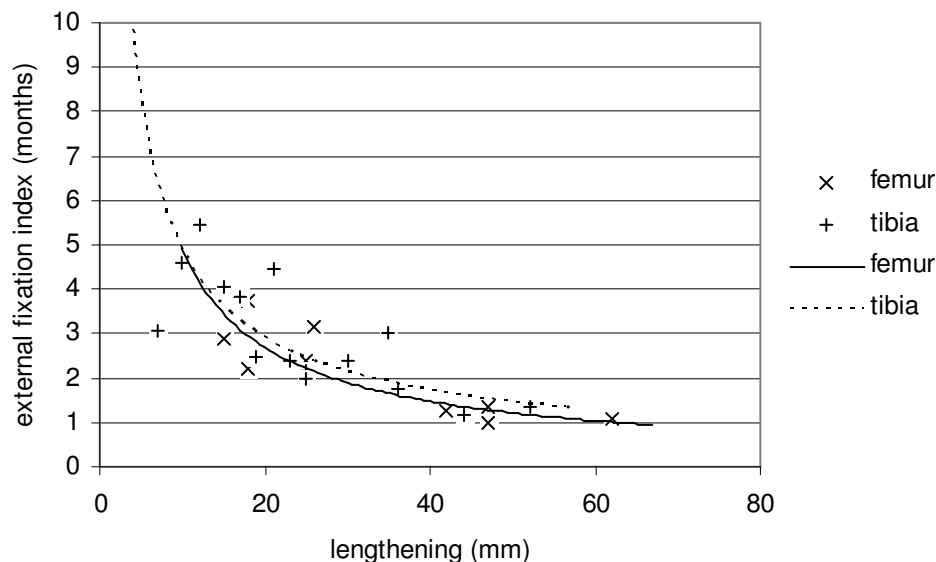


Fig. 35: External fixation index relative to amount of lengthening in all cases

	Total	Lengthening < 30 mm	Lengthening > 30 mm
Number of cases	25	18	7
Mean external fixation index	3.2	3.9	1.3

Fig. 36: External fixation index (month per cm) of lengthenings smaller and larger than 30 millimetres

The mean external fixation index of femoral corrections was lower than the index of proximal tibial and distal tibial corrections. The index of proximal tibial correction was lower than the index of distal tibial corrections⁵² (Fig. 37).

	Total	Group 1	Group 2	Group 3
Number of cases	25	9	9	7
Mean external fixation index (month)	3.2	2.1	2.8	4.7
Mean amount of lengthening (mm)	27.0	33.3	24.2	22.3

Fig. 37: Mean external fixation index of all groups

The purpose of this study was to evaluate the accuracy of treatment of femoral and tibial posttraumatic deformities using the Taylor Spatial frame. Another aim was to review the clinical outcome including the problems, obstacles and complications according to the classification of Paley. Factors were determined that influenced the duration of external fixation and the external fixation index.

In conclusion the outcome of this study encouraged us to continue the use of the Taylor Spatial Frame for correction of posttraumatic deformities. Complex multiplanar deformities could be treated simultaneously with minimal morbidity.

To avoid development or deterioration of osteoarthritis of the ankle joint due to a long period of immobilization in case of distal tibial malalignment and substantive shortening, we now today recommend the application of a tibial bi-level frame with proximal lengthening and just axial correction distally to minimize the time of immobilization of the ankle joint.

4.3 Problems, Obstacles and Complications

In order to compare difficulties that can occur in leg lengthening and deformity correction between studies of different authors, it is useful to work with a standardized classification.

Paley published a paper dealing with problems, obstacles and complications of limb lengthening by the Ilizarov technique ⁴⁰. As the TSF and the Ilizarov fixator are based upon the same biomechanical and physiological principles, the spectrum of arising principles is similar ⁵².

Difficulties that can arise during lengthening include muscle contractures, joint dislocation, axial deviation, neurologic injury, premature consolidation, delayed consolidation, non-union, pin site problems and hardware failure. Late complications are loss of length, late bowing and refracture.

Complications of any procedure can occur intraoperatively, early or late. In lengthening procedures they can appear during distraction or during fixation.

Paley introduced his classification in 1990 and performed a prospective study of 46 patients ⁴⁰.

Problems represent difficulties that arise during treatment and can be fully resolved by non-operative treatment before the end of treatment.

Obstacles equally arise during treatment and require operative treatment.

All intraoperative injuries were considered true complications and all problems during limb lengthening that were not resolved before the end of treatment were considered true complications. True complications are further subdivided into minor and major complications. Major complications interfere with the original goal of treatment.

Paley reported 60 corrections with the Ilizarov device in 46 patients. There were 35 problems (0.58 problem/correction), 11 obstacles (0.18 obstacles/correction) that required operative intervention, and 24 complications (0.40 complications/correction).

4.3.1 Complications after femoral lengthening in Congenital Femoral Deficiency (CFD) using the Ilizarov / Taylor Spatial Frame (TSF)

In 2008 a study was performed by the author of this thesis at the Orthopaedic Hospital Vienna-Speising ¹⁸. The aim was to analyze the results and the complication rate of limb lengthening and deformity correction in CFD using external ring fixation. Another goal was to evaluate the influence of different treatment protocols on the outcome.

We hypothesized that new techniques and increasing experience are able to decrease the complication rate over the observed 10-year period.

Introduction: In CFD the deformity is associated with significant limb length discrepancy, distal femoral valgus with condylar hypoplasia, AP knee instability due to cruciate aplasia, and external rotational malalignment due to femoral retroversion ^{16,33,34,53}. To correct these complex deformities, mostly circular fixators are used. Despite all attempts, a lot of complications are described in the literature ^{5,23}.

Patients and methods: We retrospectively reviewed a consecutive series of 31 patients suffering from CFD between the age of 3.3 years and 17 years (mean 9.3 y) with 35 lengthening procedures. Additionally in 17 patients a fibular hemimelia or aplasia could be found.

Surgical treatment was performed between 1998 and 2007, either the Ilizarov fixator (10 cases) or the Taylor Spatial Frame (25 cases) was used. After its introduction in 1999, the TSF was more frequently used. The attachment of the frames was done in a hybrid technique (one reference wire, half-pins). Rotational deformities were corrected with an additional proximal osteotomy (11 cases). In case of AP-instability the frame was extended over the knee (24 cases).

For preoperative planning and final assessment long standing AP radiographs in patella forward position, lateral views, orthoradiograms and standing pelvic radiograms were performed. CT-scans were used in case of rotational deformities. The range of motion of the hip and knee joint was measured preoperatively and at follow-up, complications were rated according to the principles of Paley⁴⁰.

Results: After using our exclusion criteria, 31 patients with 35 lengthening procedures were analyzed.

The mean preoperative shortening of the involved limb was 62.2 mm (32 to 125 mm). The mean shortening of the femur was 43.6 mm (14 to 107 mm); the mean tibial shortening was 11.8 mm (20 mm overlength to 48 mm short).

The mean MAD preoperatively was 18 mm lateral (42 mm medial to 70 mm lateral).

The mean mL DFA preoperatively was 84° (78° to 110°). Three patients with a LDA greater than 90 degrees had had previous operations elsewhere.

The mean MPTA preoperatively was 91° (80° to 110°).

The mean amount of lengthening at the femur was 44.3 mm (10 to 85 mm); nine patients had a simultaneous tibial lengthening of 24.2 mm (10 to 35 mm). The total amount was 50.5 mm (28 to 85 mm).

After frame removal a residual leg length difference of 11.7 mm (11 mm overlength to 60 mm shortening) could be evaluated.

Postoperatively the mean MAD was 1.2 mm medial (20 mm medial to 38 mm lateral); the mean mL DFA was 89.3° (83° to 105°), the mean MPTA was 89.7° (82° to 102°).

The mean follow-up time was 35.8 months (6 to 9 months). At that time the mean MAD was 16.2 mm lateral (18 mm medial to 90 mm lateral); the mean mLDFA 87.3° (82° to 99°); the mean MPTA was 91.4° (85° to 113°). In patients with accessory fibular hemimelia a recurrence of valgus deformity could be seen frequently. The mean duration of external fixation was 6.3 months (3.2 to 9.7 months). The mean external fixation index was 47.8 days/centimeter (21 to 127 days/centimeter).

Problems, obstacles and complications:

Pin infections could be seen as a problem in nearly all patients, at least once, and were treated with oral antibiotics.

Obstacles were evaluated in 12 cases. Three half-pins had to be removed due to infections. Nine fractures of the regenerate bone occurred after frame removal and required intramedullary rodding.

Sixteen patients showed complications. As a major complication 4 patients developed a dislocation of the knee joint during lengthening in spite of spanning the frame over the joint. This resulted in decreased range of motion of the knee.

As a minor complication 4 patients showed a mLDFA outside normal range (93° to 99°). In 3 patients it was the result of fracture and insufficient reposition of the bone. In eight patients a reduced rate of knee flexion (less than 120°) could be evaluated. Six of them had a short follow-up time between 6 and 9 months, and continued physiotherapy.

In conclusion, despite several complications, ring fixators, especially the Taylor Spatial Frame, are an effective method to treat these rare and complex deformities. The complication rate can be decreased with experience. The knowledge of possible complications can help to avoid them.

The risk of knee dislocation can be reduced by bridging of the joint with flexible hinges in combination with intensive physiotherapy. Fractures of the regenerate bone after frame removal can be avoided by prophylactic rodding. Hip dysplasia with decreased coverage of the femoral head should be treated before lengthening to avoid dislocation of the hip joint.

5 Discussion

The Taylor Spatial Frame can be used for correction of simple to the most complex multiplanar deformities using the same frame construction. Two rings are connected with six struts; a web based computer program calculates the daily strut length adjustments to perform the simultaneous six-axis correction.

The Taylor Spatial Frame can be used in the majority of aetiologies and deformities; it can be used in different age groups, as shown in the review of our complete TSF-database. The youngest patient was 2.86 years old, suffered from fibular aplasia. In this age group, even the extremely short standard struts, starting with a length of 59 millimeters, may be too long. As a solution, we started lengthening with straight rods, which were changed later to normal struts.

Patients from the CFD- and the FH/FA-group were mostly operated during toddler age or early adolescence, depending on the amount of leg length difference (LLD) and deformity. Fourteen patients suffered both from CFD (mean age 10.83 years) and FH/FA (mean age 9.98 years).

The hereditary group contains a high number of different syndromes according to the advice of the Committee on Nomenclature on Intrinsic Diseases of Bones ²².

Operations were performed routinely in the younger age (mean 15.86 years) because of progressive deformity and LLD.

The mean age of the patients from the posttraumatic group, with or without infections, was 26.20 years. Frequently the trauma was caused by motorbike or other traffic accidents; this may be the reason for the higher average of age.

Patients suffering from CPT made up a small specific group. Treatment of these patients is still a challenge because of the high rate of recurrence of pseudarthrosis even after initially achieved consolidation. A multicenter study published by the EPOS (European Pediatric Orthopedic Society) ¹⁹ in 2000 showed a healing rate with circular fixators in 75.5%, whereas plating was successful in 38%, and rodding in 42%.

In our series of 8 patients with 12 frames, just one recurrence of pseudarthrosis occurred and healed after a second Spatial Frame. The goal is to bring the patients in higher age groups with the treatment of braces ¹⁹, then the operative procedure is more successful (mean age in our series 19.57 years).

We separately analyzed a subgroup of 31 CFD-patients with 35 procedures. Lengthening and deformity correction in CFD is frequently associated with a higher complication rate, as the adjacent joints and the soft tissue formation lead to problems.

Grill and Dungal²⁰ described 2 dislocations of the hip joint in case of previous existing dysplasia in a series of 37 CFD-patients. Suzuki⁵⁴ found 5 dislocations in 12 lengthening procedures with a CE-angle less than 20°. No case of hip dislocation was found in our series. To improve the coverage of the femoral head, 3 operative procedures were prophylactically performed at the acetabulum before lengthening to prevent joint dislocation.

In the case of congenital aplasia of the cruciate ligaments, dislocation of the knee joint during lengthening may result. Especially in combination with developing a flexion contracture, there is a high risk of dislocation. Paley⁴⁰ recommended spanning the frame over the knee joint, using flexible hinges and physiotherapy, fixed in an extended position during night. In our series we extended the frame over the knee in 27 of 35 cases, because of partly or total absence of the cruciate ligaments. Of these 27 cases, 24 were fixed rigidly without hinges in an extended position. In 3 patients we used flexible hinges. Despite that prophylactic procedure 4 of 35 knee joints dislocated during the lengthening period and required further surgical treatment. All of them showed a reduced range of motion at the time of follow-up. As a consequence, since 2005 we have been using flexible hinges at the rotational center of the knee, combined with intensive physiotherapy. During the night the knee is fixed in an extended position.

In eight patients a reduced rate of knee flexion (less than 120°) was evaluated. Six of them had a short follow-up time between 6 and 9 months, and continued physiotherapy.

In CFD-patients, fractures of the regenerate bone after frame removal are a common complication described in the literature, resulting in loss of length and malalignment. Even immobilization with a spica-cast after removal of the frame does not guarantee against fractures. Danzinger¹¹ found a fracture rate after frame removal in 22% of posttraumatic cases, whereas the rate was 45% in patients with CFD.

In our series, 9 of 35 cases (25.7%) fractured after removal of the frame. These patients were treated with rodding and casting. As prevention, we now perform

prophylactic rodding after frame removal in all patients after antibiotic treatment during five days.

Axial malalignment after deformity correction may be a possible complication. In his heterogeneous group of 55 deformity patients Naqui ³⁸ described a rate of 12 patients (21.8%) with frontal deviation less than 5 degrees; 3 patients showed a deformity more than 5 degrees. In our group 4 patients (11.4%) showed a mLDFA outside normal range (93° to 99°). In 3 patients, it was the result of fracture and insufficient reposition of the bony ends.

Dahl ¹⁰ and Brownlow ⁶ described a lower frequency of complications with increasing experience. We analyzed our problems and complications in the first and the second five-year period. There was no difference assessing the superficial pin infections. Three of our four knee joint dislocations occurred in the first period, whereas just one could be found in the second period. After prophylactic rodding of the bone after frame removal, no more fractures were seen. With greater experience, however, we were able to reduce the complication rate of joint dislocation and fracture of the regenerate bone.

Manner ³² described a higher accuracy of the Taylor Spatial Frame compared to the Ilizarov fixator, especially in four-dimensional deformity correction (3 planes and shortening). In CFD-patients mostly a two-dimensional deformity (valgus and shortening) can be estimated. Therefore, in our series no significant difference could be found between the TSF and the Ilizarov group in terms of deformity correction and joint dislocation. Furthermore there were no differences between pin infections and fractures after frame removal, which can occur with both circular fixators.

In a second subgroup, 22 patients with 25 posttraumatic deformity corrections were analyzed in detail ^{17,52}. The goal was to study the accuracy of the Taylor Spatial Frame, the clinical outcome, and the rate of complications.

Tetsworth ⁵⁶ studied the accuracy of correction of complex deformities of the lower extremities with the Ilizarov fixator. In 8 of 14 cases (57%), the mLDFA was restored within 3 degrees of the normal value. In 17 of 22 cases (77%), the MPTA was restored within 3 degrees of the normal value. In 22 of 28 limbs (79%), the postoperative MAD was within normal range.

Feldman ¹⁴ reported excellent results in correction of tibia vara using the Taylor Spatial Frame. In 21 of 22 tibias (95.4%) he achieved a postoperative MPTA within 3 degrees of the normal range. The preoperative MAD was 53.9 mm medial in average, postoperative the MAD was smaller than 10 mm in all cases.

In our study, in the frontal plane, 19 of 25 joint orientation angles were outside normal range. Seventeen of these (89.4%) could be restored within 2 degrees of normal values. In the sagittal plane, 4 of 25 angles were outside normal range. All of them could be normalized within 2 degrees. MAD was restored in 15 of 18 cases (83.3%) within 7 mm of normal value.

Decreased range of motion during and after lengthening was reported by several authors.

Herzenberg ²³ investigated the range of motion of the knee joint while lengthening with the Ilizarov fixator. After a mean lengthening of 6 centimeters, 2 of 25 patients (8%) had lost more than 15 percent of their preoperative flexion at their latest follow-up examination. The average follow-up flexion was 94 percent of the preoperative flexion.

Maffulli ³¹ reported the results of femoral and tibial lengthening on knee flexion in 46 patients. After a follow-up of 41 months and a femoral lengthening of 6.6 cm and a tibial lengthening of 5.8 cm, the mean knee flexion was 94 percent of the preoperative value. Femoral lengthening showed a greater loss of flexion than tibial lengthening.

Barker ⁴ reviewed 35 patients undergoing femoral lengthening by the Ilizarov method. 88% of the patients regained full knee flexion by 6 months, 92% by 12 months, and 97% by 18 months. Analyzing knee extension, there was an average loss of 11% at the end of lengthening, which mostly regained. Two patients developed fixed knee flexion more than 40 degrees, which resulted in posterior knee subluxation.

In our study, in 19 of 22 patients (86.3%) the range of motion of the knee and ankle joint could be normalized at the last follow-up examination. One of the 9 distal femur patients (11.1%) lost more than 15 percent of his preoperative flexion.

Two of the 7 distal tibia patients (28.5%) showed reduced dorsiflexion of the ankle joint and radiological signs of osteoarthritis at the latest follow-up. Both of them had a severe varus deviation of the distal tibia in combination with substantial shortening (3.6 and 4.4 centimeters). Additionally both of them had a long period between trauma and operative correction. The foot was rigidly fixed in the frame for the whole,

long lasting lengthening period. This may be a reason for proliferation of osteoarthritis. As a consequence of this finding, now we use a bi-level tibial frame with proximal lengthening and deformity correction distally only in case of tibial shortening with distal axial deformity. So we are able to reduce the duration of immobilization of the ankle joint to prevent osteoarthritis.

Different factors can influence the consolidation of the regenerate bone, and therefore the duration of treatment.

Paley ⁴⁰ compared the results of lengthening with the Ilizarov device between 12 adult and 48 pediatric patients. Patients older than 20 years healed more slowly than younger. Children with only bone lengthening had a shorter healing time than those, who underwent lengthening and deformity correction.

Fischgrund ¹⁵ analyzed the variables in 114 patients with 140 limb lengthenings. Again, patients younger than 20 years healed faster than older ones. Metaphyseal lengthenings healed faster than diaphyseal procedures. Bi-level lengthening reduced the total external fixation time. Femoral lengthenings healed faster than in the tibia. Another important finding was that the external fixation index decreases with increasing the amount of lengthening.

In our study the femoral corrections had a lower external fixation index than in the tibia, the proximal tibia had a lower index than in the distal tibia. Patients younger than 20 years had a lower index than older ones. The external fixation index showed a huge variation in the group with mainly axial correction and short lengthening distance, whereas in lengthening procedures more than 30 mm it was similar to other reports.

In conclusion, the Taylor Spatial Frame offers several advantages compared to other lengthening devices. It allows simultaneous correction in any dimension, even in complex multiplanar deformities, following the same principles of osteogenesis than the Ilizarov fixator. A virtual hinge can be created at any position to perform the correction without difficult exchange of hinges. A web-based internet program helps to create the prescription schedule for strut adjustment, which can be handled very easily by the patients. Several studies have shown the high accuracy of the system. For those reasons, the TSF has achieved high acceptance for bone lengthening, deformity correction and fracture treatment, both in the group of surgeons and patients.

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